Lichty.

Heat Transmission Of Building Materials.

HEAT TRANSMISSION

OF

BUILDING MATERIALS

BY

LESTER CLYDE LICHTY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Lester Clyde Lichty

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C. R. Richards
In Charge of Major Work

C. R. Richards
Head of Department

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on
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HEAT TRANSMISSION
OF
BUILDING MATERIALS

PREFACE

The experiments reported in this thesis were conducted under the supervision of Professor L. A. Harding, to whom the writer is very much indebted for aid and assistance rendered during the tests.

The writer is also very much indebted to Professor C. R. Richards, Head of the Mechanical Engineering Department, and to Professor A. C. Willard, for valuable suggestions received during the tests.

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HEAT TRANSMISSION OF BUILDING MATERIALS

I. INTRODUCTION

A great variety of materials may be used in the construction of buildings, and one of the requisites of these materials, besides that of structural strength, is that of offering resistance to the flow of heat through the walls. The importance of the heat resisting properties of a wall is, of course, dependent on the nature of the service required of the building of which the wall is a part. If the building is to be used for refrigeration work, the walls must be designed to keep out heat, while in most all other constructions the object of the walls is to keep it in. However, whether the heat is transferred from the inside out or the reverse is immaterial so far as the rate of heat transfer for a given temperature difference is concerned.

Heat Transmission in General. In general there are three methods of heat transfer; that by radiation, by convection, and by conduction. In the strictly scientific sense, the energy given off from a hot body by radiation does not pass away in the shape of heat at all, since radiant energy is a form of vibration through the medium commonly known as ether which is assumed to occupy all intermolecular space. Radiation is a form of energy similar to light except that the wave lengths are different.[1] Bolton suggests that heat transferred by this method is first transformed to energy, then trans-

1. Engineering, London. November, 12, 1915.

ferred in a manner similar to that of light, and is retransformed to heat in the body or surface upon which it impinges or through which it passes.[2]

The relation between total energy of radiation and temperature, first suggested by Stefan and afterwards confirmed by Boltzmann, known as the Stefan-Boltzmann Radiation Law, may be stated as follows:

The total energy radiated by a black body is proportional to the fourth power of the absolute temperature, or

$$E = k\left(T_1^4 - T_2^4\right)$$

E being the energy radiated, k a constant depending on the units used, and T the absolute temperature.

If E is expressed in B.t.u. per square foot of the hot surface per hour and T_1 and T_2 are expressed in degrees Fahrenheit on the absolute scale, then

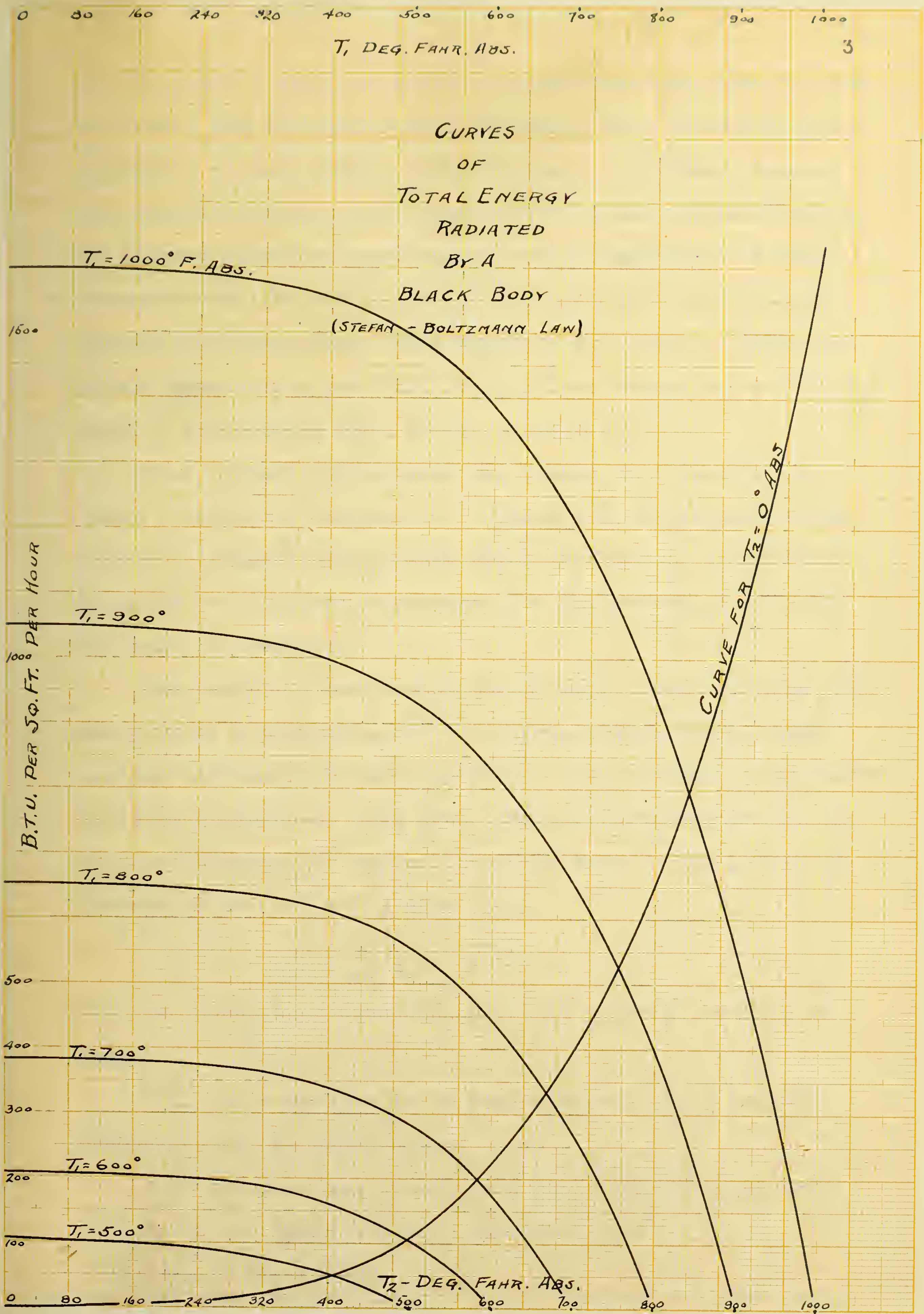
$$k = 1.6 \times 10^{-9}$$

The above constants are good only for sooted surfaces when the hotter surface is entirely surrounded by the cooler surface, the condition being that the hot surface must not "see" anything but the cold surface.

Inserting the value of k in the formula for total energy radiated by a black body the set of curves, page 3, are obtained, which show the rapid increase of radiated energy with an increase in temperature. For bodies other than black ones the value of k is different depending on the substance of which the body is composed and the nature of its surface.

Heat which is transferred from a body by means of moving

2. Journal, A. S. H. & V. E. July, 1915.
3. High Temperature Measurement, Burgess.



CURVES
OF
TOTAL ENERGY
RADIATED
BY A
BLACK BODY
(STEFAN - BOLTZMANN LAW)
T_1 DEG. FAHR. ABS.
0 80 160 240 320 400 500 600 700 800 900 1000
B.T.U. PER SQ. FT. PER HOUR
1500
1000
500
400
300
200
100
0
T_1 = 1000° F. ABS.
T_1 = 900°
T_1 = 800°
T_1 = 700°
T_1 = 600°
T_1 = 500°
CURVE FOR T_2 = 0° ABS
T_2 - DEG. FAHR. ABS.
0 80 160 240 320 400 500 600 700 800 900 1000

air in contact with its surface is said to take place by convection. Peclet[4] states that the loss from convection is independent of the nature of the surface of the body, and of the absolute value of the temperature of the surrounding air; it depends solely on the excess of the temperature of the body over that of the surrounding air and on the form and dimensions of the body. The rapidity with which circulation of air takes place over the surface is a factor to be reckoned with in determining the loss by convection.

Heat transferred between two bodies that touch each other is said to take place by conduction, which applies as well to a single body through which the heat is transmitted by means of the close arrangement of the molecules of which the body is composed.

The amount of heat conducted through a unit of area from one part of a body to another is proportional to the temperature difference of the two parts, proportional to the conductivity of the body, and also inversely proportional to the distance between the two parts of the body. This law is expressed by the following equation:

$$H = \frac{c}{d}\left(T_1 - T_2\right)$$

Where H is the heat conducted per unit of area per unit of time.

c is the conductivity of the material, which varies somewhat with the temperature.

d is the distance between the two parts of the body.

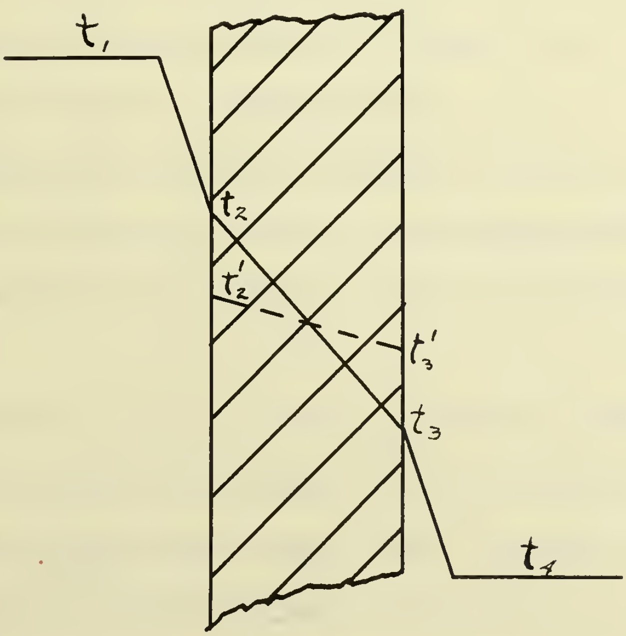
T_1 is the temperature of the hotter part.

4. Traite de la Chaleur.

T_2 is the temperature of the colder part.

That the conductivity of some materials varies considerably with the mean temperature is shown by the results of tests reported in Bulletin No. 36, Engineering Experiment Station, University of Illinois. Tests performed by Grober and Nusselt[5] prove that conductivity increases almost in proportion to the density and that it varied somewhat with the absolute temperature. Peclet states that dampness greatly increases the conductivity of insulating materials, a fact now well known to all refrigerating engineers. One of the most important problems in the construction of insulation walls is to prevent the entrance of moisture.

Diagram Illustrating Heat Transfer Through A Wall



A drop in temperature occurs between the air temperature (t_1) and the temperature of the wall (t_2) with which the air

5. Mechanical Refrigeration, Macintire.

is in contact, this drop occuring within a small layer or air film close to the surface. Dalby[6] suggests that there is probably a further drop of temperature head, represented by the distance between t_2 and t_2', which is required to force the flow across the surface where the gas film is in contact with the wall, corresponding to a potential difference at a joint in an electric circuit. This is usually referred to as contact resistance.[7] Contact resistance is such a resistance that cannot be measured by thickness, but requires an appreciable amount of potential difference to produce an appreciable amount of current flow whether the potential difference be volts or degrees and whether the current flow be amperes or thermal units.

The transmission of heat from the air at temperature (t_1) to the wall at (t_2) takes place partly by radiation and partly by convection, the coefficients of which will be designated by the letters R and c, respectively.

The transmission of heat through the wall from the inside surface to the outside one is accomplished by conduction alone, the coefficient of which will be designated by the letter C.

The transfer of heat from the outside surface to the outside air is assumed to take place in an exactly similar manner to that on the inner side of the wall, except that the transfer takes place in the opposite direction.

Knowing that the amount of heat transferred from the inside air to the inside surface of the wall, the heat conduct-

6. Heat Transmission, Institution of Mech. Eng. Oct. L909.
7. Refrigerating World, p. 29, September, 1914.

ed through the wall, and that given off by the outside surface of the wall are equal, the following relation between the coefficients is readily derived:

By definition

$$H = \mu (t_1 - t_4)$$

$$H = (R_1 + c_1)(t_1 - t_2)$$

$$H = \frac{C}{x}(t_2 - t_3)$$

$$H = (R_2 + c_2)(t_3 - t_4)$$

from which

$$\frac{1}{R_1+c_1} + \frac{1}{R_2+c_2} + \frac{x}{C} = \frac{t_1 - t_2}{H} + \frac{t_2 - t_3}{H} + \frac{t_3 - t_4}{H}$$

$$= \frac{t_1 - t_4}{H}$$

but $$\frac{1}{\mu} = \frac{t_1 - t_4}{H}$$

hence $$\frac{1}{\mu} = \frac{1}{R_1+c_1} + \frac{1}{R_2+c_2} + \frac{x}{C}$$

or $$\mu = \frac{1}{\frac{1}{R_1+c_1} + \frac{1}{R_2+c_2} + \frac{x}{C}}$$

H being the heat loss per square foot, B.t.u.

u the transmission coefficient, air to air.

x the thickness of the wall in inches.

Reliable experimental data are lacking for both the radiation and convection coefficients of the various materials of building construction. It is difficult to separate, in experimental work, the heat that is given off by radiation from that which is removed by convection. Consequently it is customary to combine the coefficients of radiation and convection for any one surface, in which case, designating the com-

bined coefficients by K_1 and K_2 for the inside and outside walls respectively, the relation of the coefficients becomes:[8]

$$\mu = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \frac{x}{C}}$$

Purpose of the Investigation. From a consideration of the above theory of heat transmission of materials, it is evident that in order to apply the heat transmission formula to any wall, it is only necessary to know, within fairly close limits, the values of the various coefficients of the materials entering into the construction of the wall.

The purpose of the first part of this investigation is to determine the various coefficients of heat transmission for a number of common building materials.

For some time it has been known that the velocity of air moving over the surface of a wall has an effect on the heat transmission through the wall. All heating and ventilating engineers make an allowance for increased heat loss of buildings exposed to wind. Up to the present however this allowance has been merely a guess, usually placed high enough to be safe. It is also thought that humidity is a factor affecting the heat loss from walls.

The purpose of the second part of this investigation is to determine the effect of wind or air velocity, and the combined effect of air velocity and humidity on the outside surface coefficient.

Previous Heat Transmission Investigations. The French physicist Peclet was the pioneer in the investigation of heat

8. Mechanical Equipment of Buildings, Harding and Willard.

transmission. His experimental work has been the basis of practically all the treatises which have since been written. The work of Peclet was followed by investigations conducted under the auspices of both the Austrian and German Governments, and by various experiments throughout this country.

Probably the best equipped thermal testing plant in this country is that of the Armstrong Cork Company located at Beaver Falls, Pa. The plant consists of a well insulated room, inside of which the air is maintained at any desired temperature by means of refrigerating machinery. The test box, made of the material to be tested, is placed in the center of this room, the Hot Air Box method of testing being used. In tests made at this plant no attempt has been made to determine surface temperatures as only transmission coefficients for the various wall constructions were desired.

A thermal testing plant, similar to that of the Armstrong Cork Co., is located at Pennsylvania State College, where various heat transmission tests have been run during the past six years. At present, in the work being done at this testing plant, temperatures are measured by means of platinum resistance thermometers, both inside and outside the test box as well as in the walls, and on their surfaces.

Recently a series of tests for determining the relative merits of ice house construction were carried on at the Worcester Polytechnic Institute.[9] Nine small ice houses using different wall constructions were built, and used as test boxes. The method of testing used was similar to that of the

9. Refrigerating World, June, 1915.

Ice Box method. A comparison of the various types of wall construction used was obtained from the amount of ice melted in each ice house.

The latest heat transmission tests of importance are those of L. B. McMillan run at the University of Wisconsin.[10] A number of steam pipe coverings were investigated to determine their respective heat insulating properties. For determining the temperature of the air in the test room high grade mercury thermometers were used, and after considerable experimenting it was decided to use copper-constantan thermocouples for the pipe temperatures. In this connection the potentiometer method of measuring the electro motive force of the couples was used. To embed the thermocouple junction in the pipe, a chip was raised on the surface of the pipe, the thermocouple junction held underneath and the chip forced down, thus holding the couple in contact with the metal pipe.

That the rate of heat transmission of any substance is affected by the rate of flow of a fluid over its surface has been known for some time. Various hot blast heater, boiler tube, condenser, and other similar experiments have been run to determine the effect of rate of flow, of the fluids concerned, on the heat transmission coefficients of the apparatus tested.

Recently an attempt was made by W. H. Whitten and R. C. March[11] to establish a standard coefficient for heat losses affected by wind movement. Their deductions included the leakage which varies with the structures considered.

10. The Journal, Am. Soc. of M. E., January, 1916.
11. The Journal, Am. Soc. of H. & V. E., October, 1915.

The work of the Engineering Experiment Station of Pennsylvania State College in regard to the transmission of heat through various building materials has been devoted to a study of the effects produced by varying velocities and humidity of air over the material tested.[12]

In the air velocity tests, air was blown over one side of the test box, for which purpose three different arrangements were used. First air was blown from spouts, the result of which was an uneven flow over the surface. Next, a fish tailed affair was used to correct the uneven flow of air. To shield the other sides of the test box from eddy currents a galvanized iron shield was placed around the surface being tested.

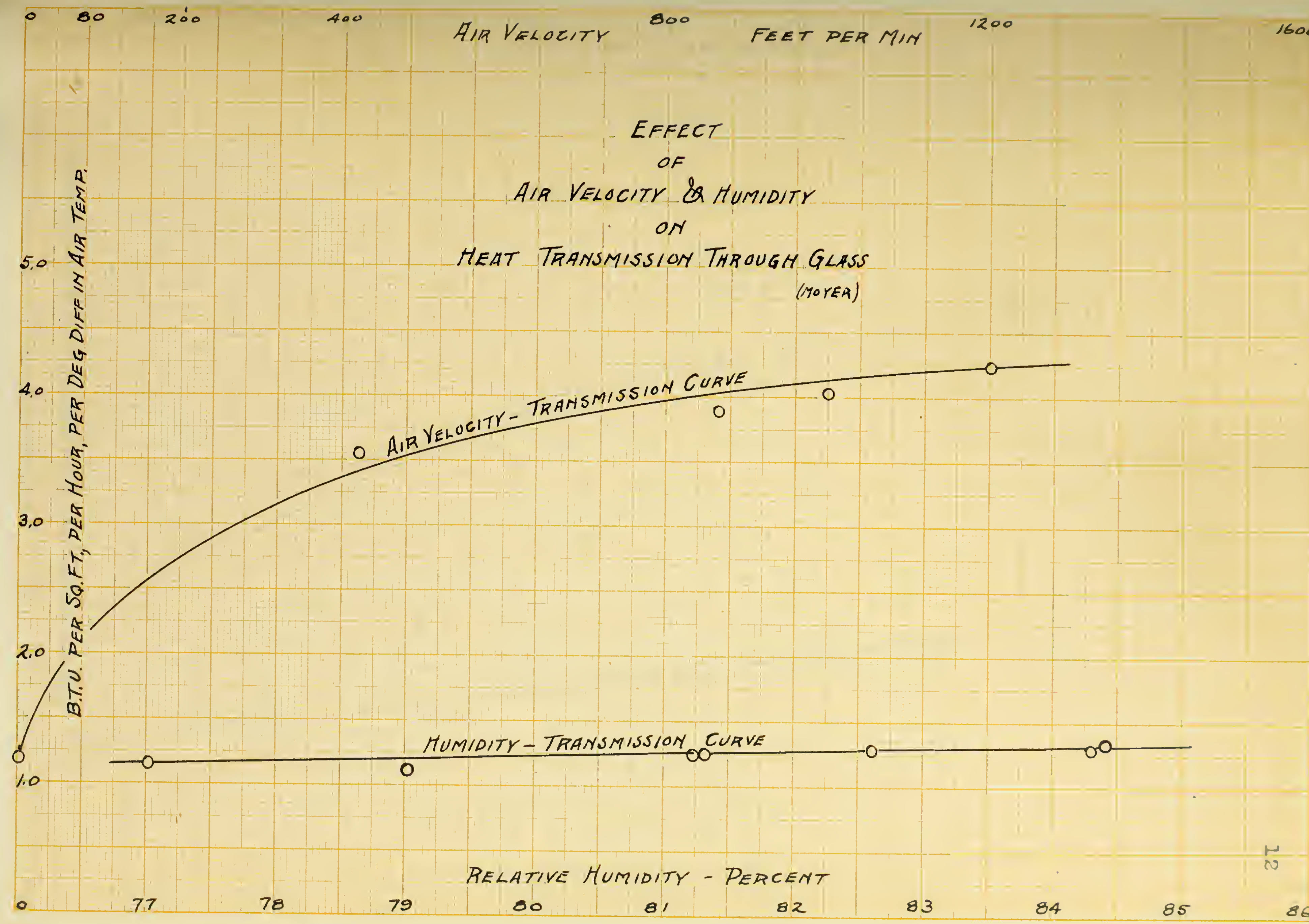
Results of the tests on glass are given by curves, page 12, which show the effect of air velocity and humidity on the rate of heat transmission.

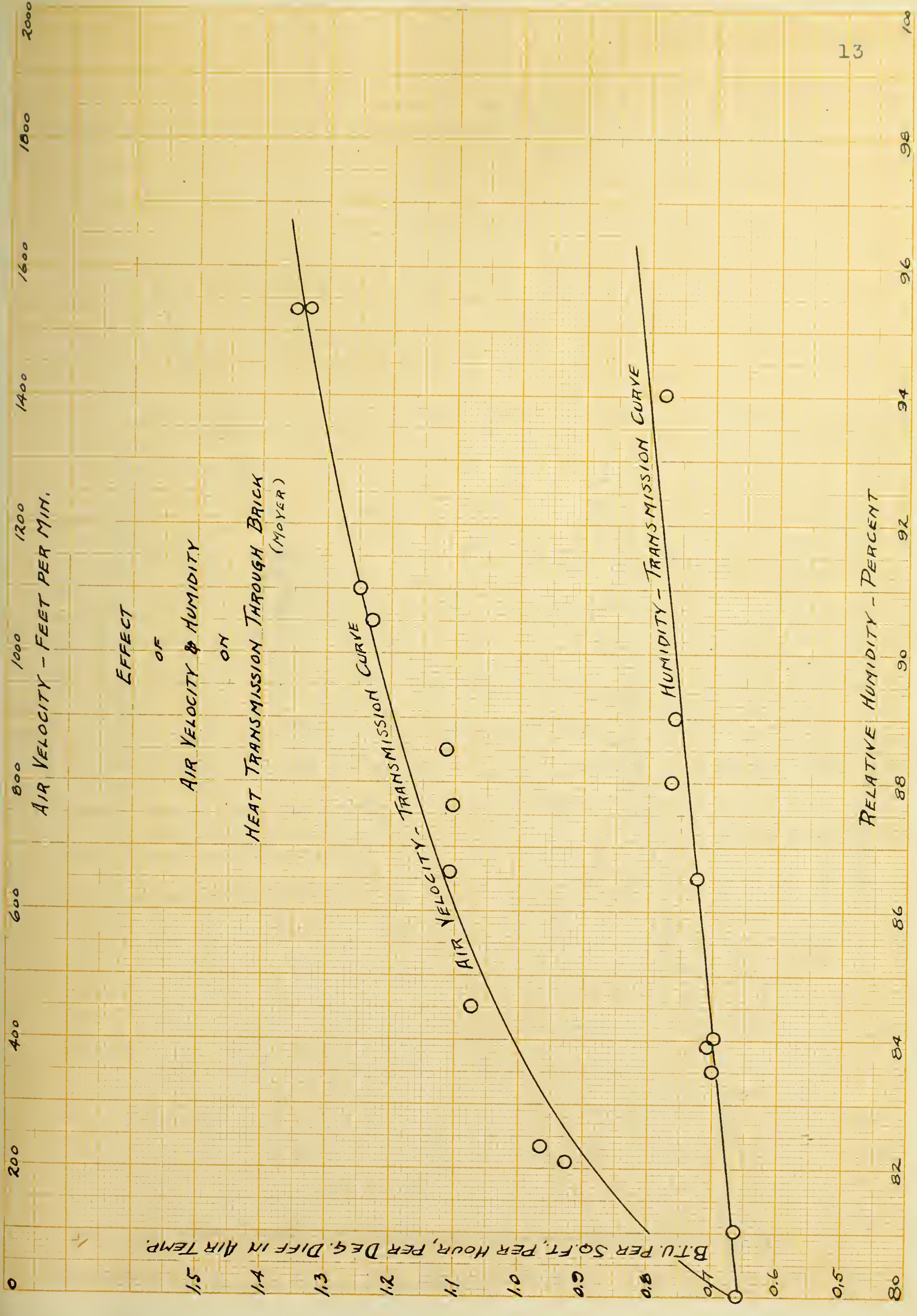
The results of corresponding tests on brick are given by curves, page 13. In each case the air velocity curves are corrected to an assumed standard of 80% relative humidity.

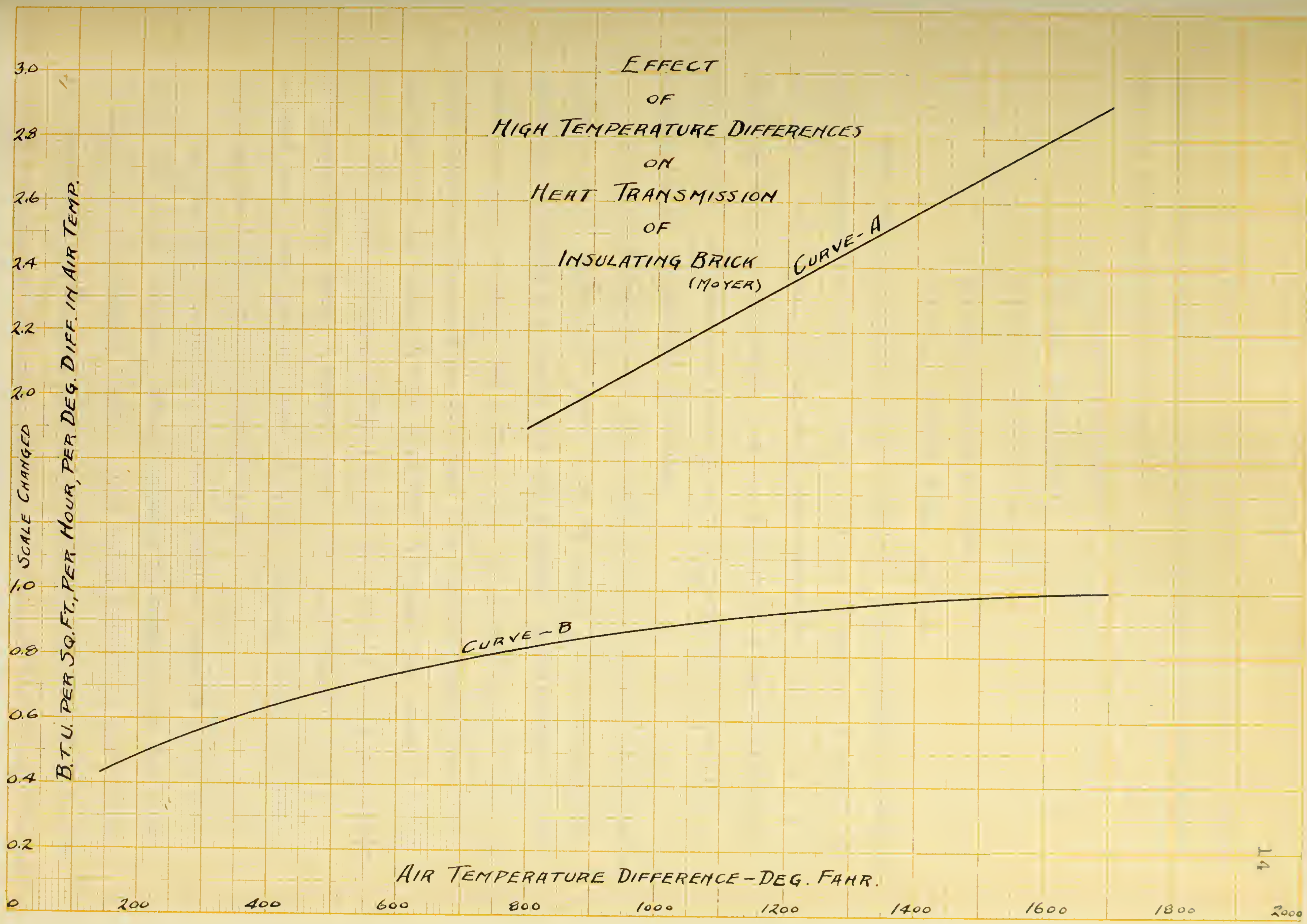
Tests were also run to determine the effect of high temperature differences on the heat transmission of insulating brick. All the tests were run under still-air conditions, the surfaces tested being subjected only to the velocity created by natural circulation and the internal temperature maintained from 800 to1700 degrees Fahrenheit. The results of these tests are given by curve A, page 14.

Similar tests on Nonpareil insulating brick give the results shown by curve B, page 14.[13]

12. Journal, Am. Soc. of H. & V. E., 1916.
13. Armstrong Cork & Insulation Company.


Effect
of
Air Velocity & Humidity
on
Heat Transmission Through Glass
(Moyer)
Air Velocity Feet per Min
0
80
200
400
800
1200
1600
B.T.U. per Sq. Ft., per Hour, per Deg. Diff in Air Temp.
1.0
2.0
3.0
4.0
5.0
Air Velocity - Transmission Curve
Humidity - Transmission Curve
Relative Humidity - Percent
0
77
78
79
80
81
82
83
84
85
86


EFFECT
OF
AIR VELOCITY & HUMIDITY
ON
HEAT TRANSMISSION THROUGH BRICK
(MOYER)
AIR VELOCITY - FEET PER MIN.
0
200
400
600
800
1000
1200
1400
1600
1800
2000
RELATIVE HUMIDITY - PERCENT
80
82
84
86
88
90
92
94
96
98
100
B.T.U. PER SQ. FT. PER HOUR, PER DEG. DIFF IN AIR TEMP.
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
AIR VELOCITY - TRANSMISSION CURVE
HUMIDITY - TRANSMISSION CURVE



EFFECT
OF
HIGH TEMPERATURE DIFFERENCES
ON
HEAT TRANSMISSION
OF
INSULATING BRICK
(MOYER)
CURVE-A
CURVE-B
B.T.U. PER SQ.FT., PER HOUR, PER DEG. DIFF. IN AIR TEMP.
SCALE CHANGED
AIR TEMPERATURE DIFFERENCE-DEG. FAHR.
3.0
2.8
2.6
2.4
2.2
2.0
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Various methods have been followed in the tests to determine the heat transmission through building materials, which may be classified as follows:[14]

(1) Ice Box method.

(2) Oil Box method.

(3) Cold Air Box method.

(4) Hot Air Box method.

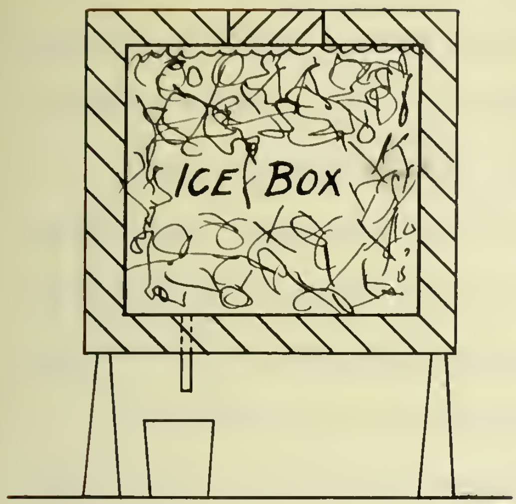
(5) Flat or Hot Plate method.

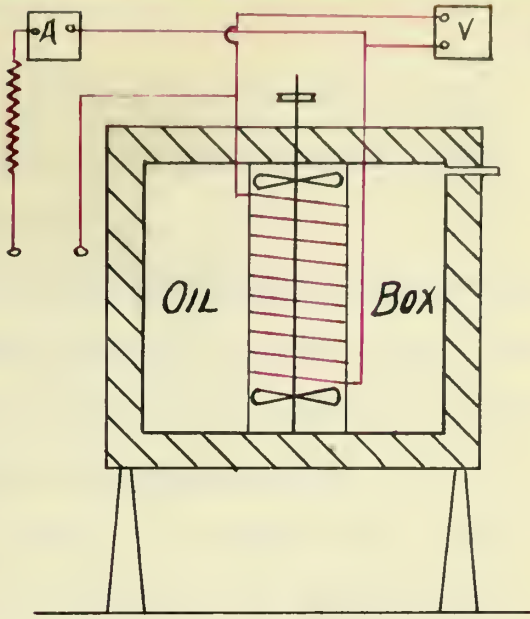
The Ice Box method is the simplest one employed in making heat transmission tests. Ice is placed inside of a metal box or cube, outside of which is placed the material to be tested. Knowing the rate at which the ice melts, the temperature of the melting ice and the outside air temperature, the heat transmission is readily obtained.

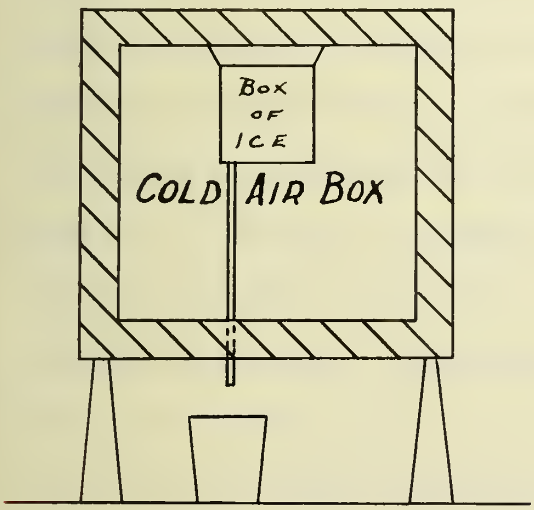
The disadvantages of this method are: (1) Ice has a tendency to melt in pockets and to be retained in the box after melting, causing low results; (2) Frequent additions of ice must be made to keep the box as full as possible; (3) The inside temperature used is not the true inside temperature on account of the temperature gradient through the walls of the metal box thus causing coefficients to run low; (4) The range of temperature drop, through which the material is to be tested, is fixed unless some outside means be used for regulating the outside air temperature.

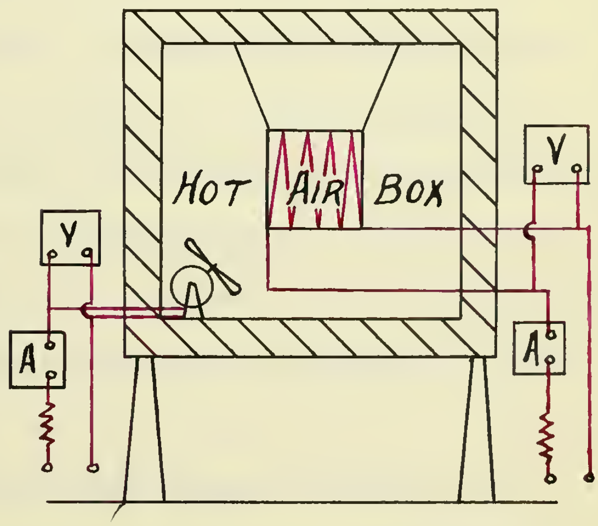
In the Oil Box method a metal box is covered with the material to be tested. Oil is placed inside of the box and is kept at the desired temperature by means of an electrical

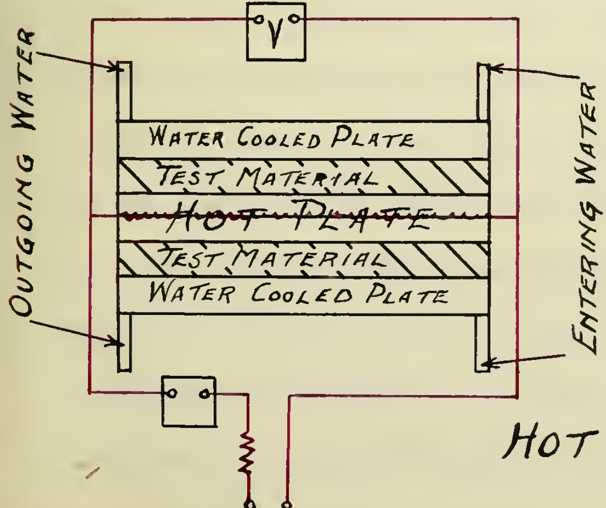
14. Nonpareil Corkboard Insulation, Armstrong Cork & Ins. Co.

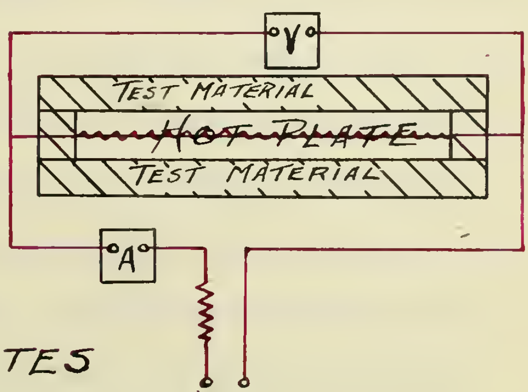

ICE BOX


A
V
OIL
BOX


BOX
OF
ICE
COLD AIR BOX


V
HOT AIR BOX
V
A
A


V
OUTGOING WATER
ENTERING WATER
WATER COOLED PLATE
TEST MATERIAL
HOT PLATE
TEST MATERIAL
WATER COOLED PLATE


V
TEST MATERIAL
HOT PLATE
TEST MATERIAL
A

HOT PLATES

heater, made of resistance wire immersed in the oil. The amount of heat transmitted through the material under test is determined from the electrical input.

With the exception that the range of temperature through which the tests may be run is much larger, and that there is no addition of material to that in the metal box, this method has the same disadvantages as the Ice Box method.

In the Cold Air Box method a box of cracked ice, hung near the top on the center line of the box, is substituted for the electrical heating element. The melting of the ice maintains the temperature of the air in the box lower than that of the air outside of the box. Suspending the ice box near the top of the test box is supposed to cause natural circulation to maintain the inside air temperature very nearly uniform. The heat transmitted is determined by weighing the the amount of ice melted. Since the control of the temperature inside of the box is not good this method is inferior to the Hot Air Box method.

The test box, for the Hot Air Box method, is made entirely of the material to be tested, unless the material is such that a skeleton frame work is necessary to provide strength for the structure. The heat is supplied by electrical means, either a resistance coil or a bank of lamps being used. Usually a fan is employed inside the test box to circulate the air and thereby maintain its temperature constant throughout the interior of the box. The amount of heat transmitted through the material, in this case, is determined from the combined electrical input to the heater and the fan motor.

This method or a modification of it is considered the best to employ in testing materials for heat transmission losses. The use of the fan, however, is objectional if a determination of the inside coefficient (K_1) is to be made, as the velocity of the air over the inside surface increases the value of K_1 somewhat. In test specimens of large dimensions the fan is necessary if the interior air is to be maintained at a uniform temperature throughout.

In the Flat or Hot Plate method the heating element consists of an electric grid, made of resistance wire placed between asbestos sheets. The material to be tested is placed on both sides of the grid, being in contact with it. Outside of the test material is placed two hollow flat plates which are kept at a constant temperature by the circulation of water through them. All of the heat, except that lost from the edges in some plates, goes through the test material into the water-cooled outside plates. In some hot plates no water-cooled outside plates are used, the edges being covered with the test material, and thus the heat passes through the test material only. The heat lost is measured by the electrical input and the temperature difference between the inside and outside surfaces, usually by electrical means. Knowing the dimensions of the plate the conductivity of the specimen is readily determined.

The loss of heat from the edges, in the one case, is an unknown amount, and according to one authority is not only considerable but somewhat variable in amount, depending on the nature and thickness of the material tested. A correction

for this edge loss must be made, the accuracy of which is somewhat uncertain. When using the water-cooled plates, only the conductivity can be determined, while without them the outside surface coefficient can also be obtained. In neither case can the transmission coefficient (air to air) be obtained.

Using any of the box methods of testing, the determination of the heat transmission coefficient, u, is a comparatively simple matter, but in order to determine any of the other coefficients an accurate determination of surface temperatures must be made. Various schemes for temperature measurement have been employed for this purpose. Oil wells for mercury thermometers have been sunk in the surface of the material, the center line of the oil well lying in the plane of the material being tested. Mercury thermometers have been fully embedded in the material, half-way embedded, and fastened on the surface in attempts to determine the true surface temperature. Experiments show that the accuracy with which mercury thermometer determinations of surface temperatures can be made depends almost entirely on the dimensions and the nature of the test specimen. In other words the temperature gradient through the material is the determining factor. If the material being tested is quite thick, with a corresponding small temperature drop per inch through the material, the displacement of the center line of the thermometer with regard to the surface of the material is much less important than is the case with a comparatively thin test specimen and its correspondingly steeper temperature gradient.

Dalby further complicates the matter by his suggestion, previously mentioned, that there is probably a further drop of temperature head occuring just at the surface of the material which is required to force the flow of heat across the surface. However, the temperature head required to cause the flow of heat through the material is the difference between the temperatures at each end of the temperature gradient through the material itself.

The temperature gradient through the material is usually assumed to be a straight line, which suggests the possibility of determining the surface temperatures by determining the temperatures at two different points along this gradient and then solving either graphically or analytically for the surface temperatures. But most building materials are not homogeneous enough to warrant the straight line assumption. This depends somewhat on the density of the material in question.

Attempts to determine surface temperatures, by means of platinum discs held against the surface of the material in question, have been made at the Engineering Experiment Station at Pennsylvania State College.

II. OUTLINE OF THE INVESTIGATION

Description of the Apparatus. The Hot Air box method of testing being considered the best it was decided to use this method for testing the materials. The box or column was built entirely of the material to be tested except in cases where means of support were needed. In order to get convection conditions similar to those in actual practise the columns were built about the height of a room. The test boxes were supported on small piers, thus allowing air around practically all parts of the box.

The heating element was composed of Yankee silver resistance wire, spirally wound with increasing pitch from bottom to top, upon a wooden frame support placed inside the column. With this method of heating it was found after considerable experimenting that the air temperature was maintained the same as is found in rooms, that is somewhat warmer near the ceiling than at the floor line.

A voltmeter across the terminals of the resistance heating coil, an ammeter in the line, and a water box to regulate the current constituted the apparatus necessary to regulate and determine the heat input into the box. All electrical instruments were accurately calibrated against standard meters of the Electrical Engineering Department.

Air and surface temperatures were measured either with mercury thermometers and thermocouples or with thermocouples

alone. All mercury thermometers were carefully calibrated against a standard Centigrade thermometer of known accuracy.

A diagrammatic sketch of the apparatus used for determining the various coefficients is shown by Plate I, page 23. Only one thermocouple circuit is shown in the diagram for the sake of simplicity.

For the Air Velocity Tests, in addition to the apparatus shown by Plate I, a hood shown by Plate II, page 24, was placed over the column. This hood, placed so that the column was centrally located inside, was connected to a Siricco blower by means of a 24-inch duct about 30 feet long. A variable speed Direct Current motor belt-connected to the Siricco blower furnished the means to provide the various velocities of air flow over the surface of the column being tested. By means of dampers in the hood the velocity of the air was maintained constant over the four sides.

A Pitot tube and a piezometer ring were used to determine the quantity and consequently the velocity of the air over the surface of the test column.

Thermocouples and their Calibration. The thermocouple is the temperature measuring device which is best suited for the determination of surface temperatures. The junction, when just imbedded in the surface of the material, indicates as near the surface temperature as it is possible at the present time to obtain. The accuracy of the temperatures determined in this manner is also dependent on the temperature gradient through the material. But due to the difference in dimensions between a thermocouple junction and the thickness of the ma-

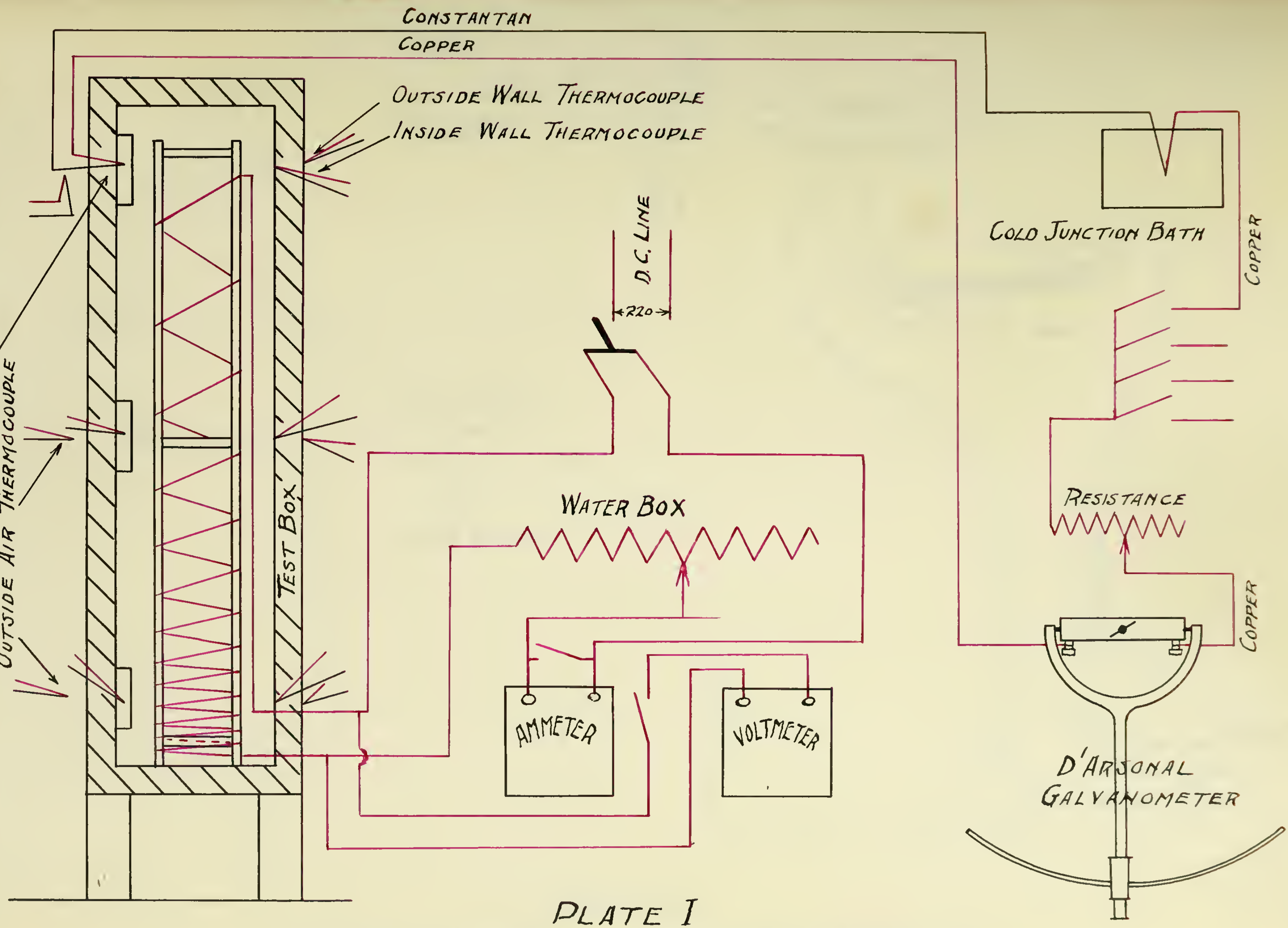


Plate I
Diagram of Apparatus for Heat Transmission Tests

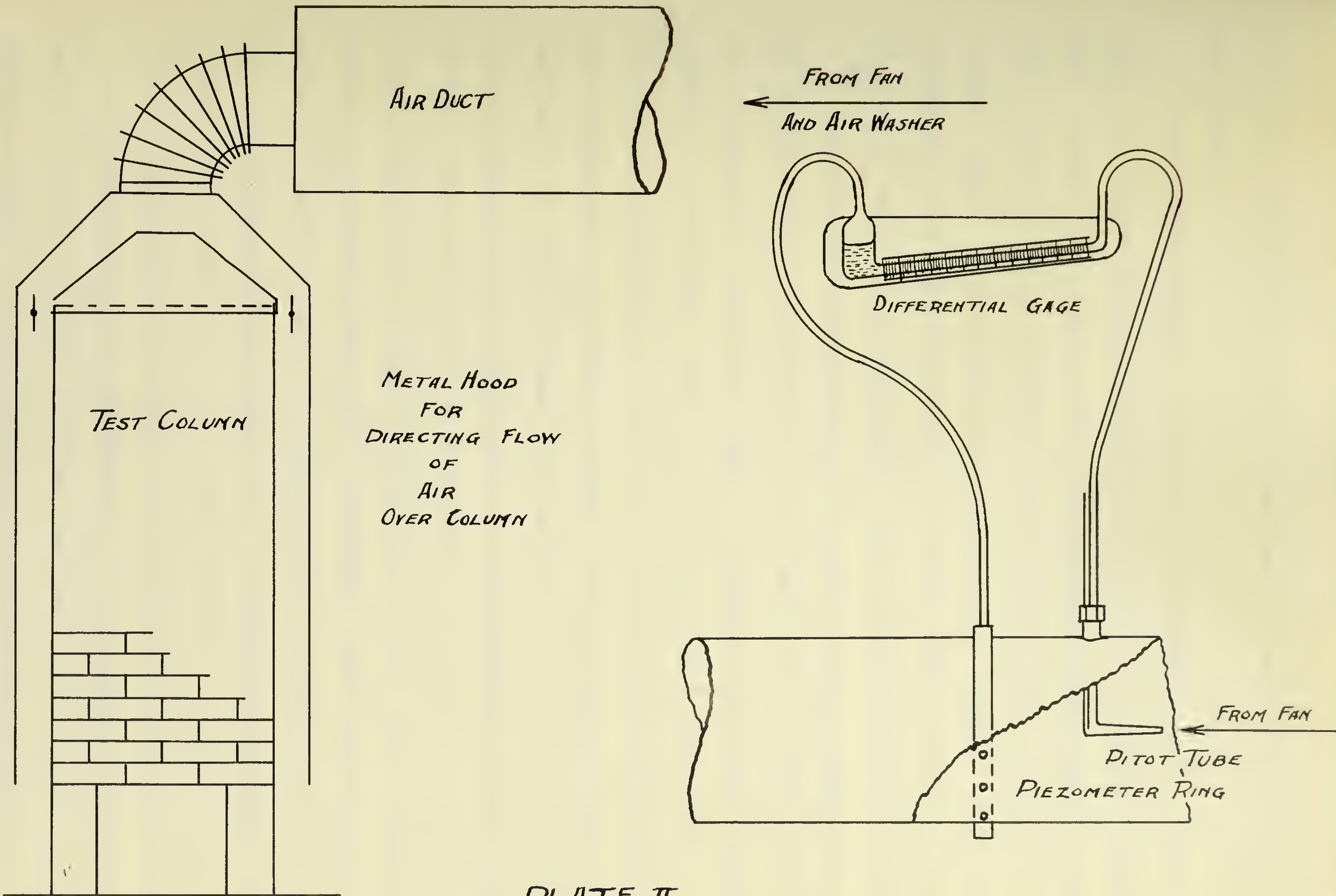


PLATE II

DIAGRAM OF APPARATUS FOR WIND TESTS

aterial to be tested, this is reduced to comparative insignificance.

The thermocouples were made up of copper and a nickel alloy of copper termed constantan, # 25 B. & S. gage, double silk covered wire being used. The junctions were made by fusing the ends of the two different wires together in the flame of a blast lamp. Each junction was placed in a glass tube, closed at one end and filled with oil, the two wires being insulated from each other by a small glass tube around one of the wires.

Calibrations were made with a cold junction temperature of 70 deg. Fahr., the hot junction temperature being controlled by means of a hot water bath. In series with each couple, by means of switches, was placed a resistance and a Type H D'Arsonal galvanometer. The deflection method of measuring the temperature difference between the cold and hot junctions was used. In order to make this method as accurate as possible, all calibrations were made with the galvanometer balanced and set in position on the concrete pier, in which position it remained without any change through the set of tests with which any set of thermocouples were connected. That the deflection method is very reliable if proper care is taken is shown by the fact that this method was used in recently completed set of experiments on the rate of heat transfer through boiler tubes, conducted by the Babcock & Wilcox Co. at Bayonne, N. J.

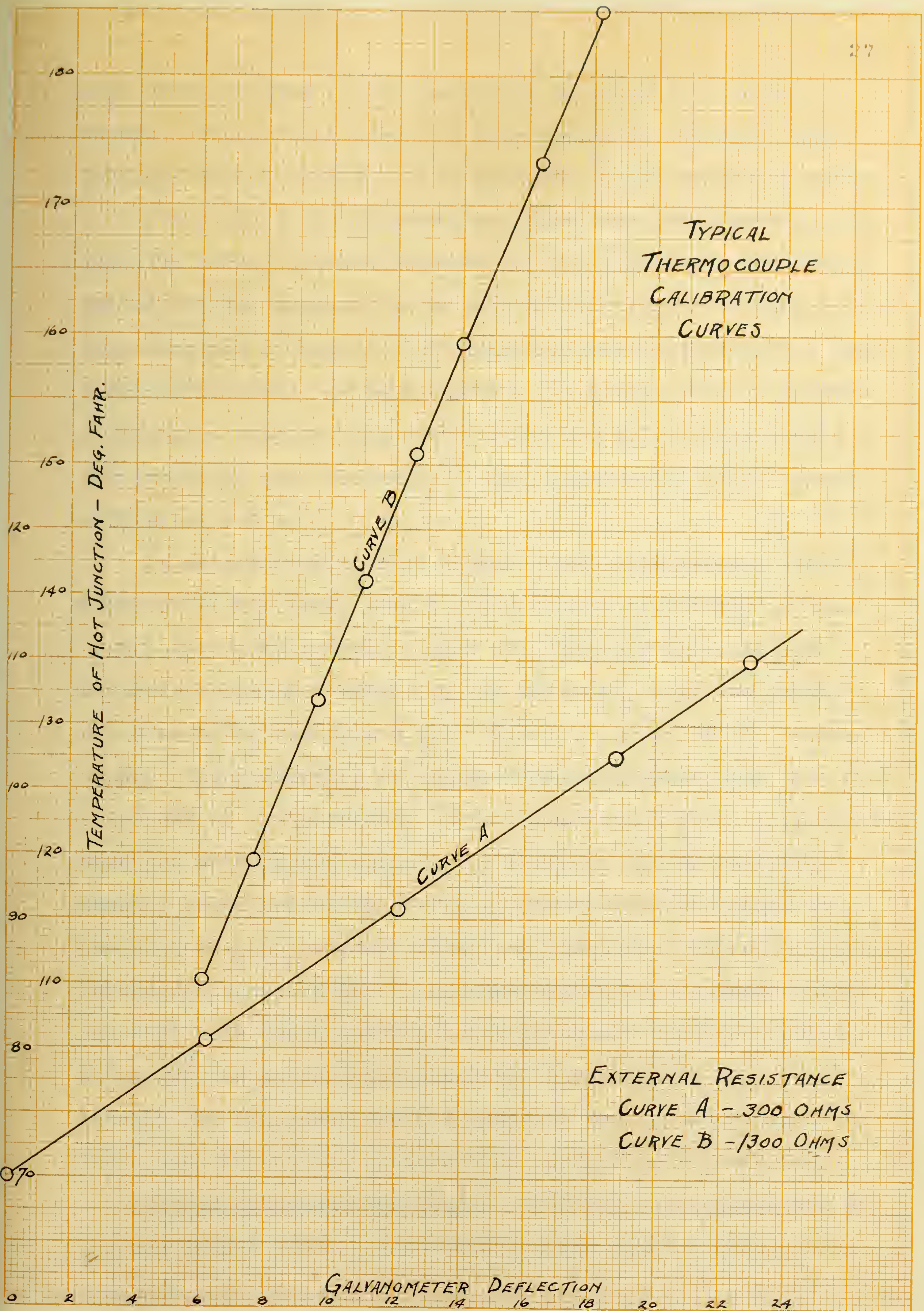
In calibrating thermocouples it is customary to hold the temperature of the cold junction constant, at a predetermined point, and vary the hot junction temperature and note the deflection of the galvanometer. Owing to the slight inconven-

ience of keeping the cold junction at the same temperature at which it was calibrated, some experimenters prefer to run a series of calibrations varying the temperature of the cold junction over the range it is expected to vary during the test.

Another method of procedure is to calibrate as in the first case, holding the cold junction at a certain temperature. Then with a fixed hot junction temperature the cold junction temperature is changed to a point above and one below the original temperature during the calibration. The three readings or deflections are plotted and the equation of the curve determined, from which the correction for the cold junction temperature is readily made.

The first method was followed during these experiments. A typical set of thermocouple calibration curves is shown on the curve sheet, page 27. It will be noted that the curve A, of the lower temperature differences, is obtained with 300 ohms external resistance in the circuit, while 1300 ohms were used to obtain the curve of higher temperature differences. This method gives a larger deflection for the lower temperatures than would otherwise be obtained with a single fixed resistance in the circuit, large enough to keep the deflection corresponding to the highest temperature to be measured within the range of the galvanometer.

After calibration the so-called hot junctions were removed from the glass containers and fastened in position, either on the surfaces of the material to be tested or in the air about one-inch from the surface. All thermocouples and mercury thermometers used for determining air temperatures


TYPICAL THERMOCOUPLE CALIBRATION CURVES
TEMPERATURE OF HOT JUNCTION - DEG. FAHR.
GALVANOMETER DEFLECTION
CURVE A
CURVE B
EXTERNAL RESISTANCE
CURVE A - 300 OHMS
CURVE B - 1300 OHMS
180
170
160
150
120
140
110
130
100
120
90
110
80
70
0
2
4
6
8
10
12
14
16
18
20
22
24

were shielded from direct radiation by means of a paper shield. Those to be used for determining the surface temperatures were fastened to the surfaces in the following manner:

For wood, a thin shaving was glued over the junction, the junction being somewhat embedded in the surface of the material before the application of the thin shaving. For the materials composed of asbestos the junction was covered with a thin sheet of asbestos, or held against the surface with a mixture of powdered asbestos and water. For the vitreous materials the junctions were fastened to the surface with a thin layer of plaster paris.

In determining surface temperatures with mercury thermometers it was found that by embedding the thermometer in a trench just deep enough so that the thermometer would lie entirely below the surface of the material, that the temperature recorded would be higher than that given by the thermocouple, the difference of course being dependent upon the thickness of the material. Also it was found that if the thermometers were placed against the surface, all of the thermometer being out of the surface, yet covered and stuck to the surface as previously described, that the temperature recorded was somewhat lower than that given by the thermocouple. And that with comparatively thick materials that the temperatures of the thermometers and the thermocouples were practically the same when the thermometers were so embedded that their axes lay in the plane of the surface of the material.

<u>Method of Conducting Tests</u>. To bring the temperature of the air inside of the test column to the desired point, con-

siderable current was allowed to flow through the resistance heating coil. As the rising air temperature approached the desired point the current was decreased until just the right amount was flowing to maintain the desired temperature. In all cases sufficient time, from 24 to 72 hours, depending on the material and its thickness, was then allowed to elapse in order to insure constant heat flow conditions. Readings of thermometers, thermocouples and electrical instruments were then taken at intervals of 30 minutes. From five to seven readings were taken during each test, local conditions determining the duration of the tests. Usually three or four tests were run on each material, maintaining various air temperature differences for each test. In most cases both mercury thermometers and thermocouples were installed for each test which made possible the running of both tests at the same time, so that a direct comparison might be made.

The Air Velocity Tests were conducted in a similar manner, and in addition a traverse of the air duct was made during each test, the fan speed recorded and the exit velocity of the air over the four sides of the column checked with an anemometer at the customary 30 minute interval. The relative humidity of the air was determined for each test.

In the combined Air Velocity and Humidity Tests, the humidity of the air as it left the air washer was also recorded. The air washer made it possible to provide air at practically 100% relative humidity for the combined Air Velocity and Humidity tests.

Calculations. The readings, taking during a test, for

each thermometer, thermocouple or electrical meter were first averaged, then corrected according to the calibration, after which the corrected averages for any one part, such as the outside surface temperatures, were then averaged, the result being the outside surface temperature in the case mentioned. From these final temperatures the various drops, air to air, wall to wall, air to wall, and wall to air were determined.

The heat loss was determined from the electrical input by means of the following relation:

Volts x Amperes x 3.412 = B.t.u. loss per hour.

Knowing the heat input the various coefficients were determined from the following relations:

$$\mu = \frac{H}{S_m}(T_1 - T_4)$$

$$K_1 = \frac{H}{S_1}(T_1 - T_2)$$

$$K_2 = \frac{H}{S_2}(T_3 - T_4)$$

$$C = \frac{Hx}{S_m}(T_2 - T_3)$$

in which,

S_m is the mean area of the surfaces, in sq. ft.

S_1 is the inside area of the test box, sq. ft.

S_2 is the outside area of the test box, sq. ft.

H is the total heat loss of the box.

T_1 is the inside air temperature.

T_2 is the inside wall temperature.

T_3 is the outside wall temperature.

T_4 is the outside air temperature.

S_m is taken as the arithmetrical mean of S_1 and S_2.

In the Air Velocity Tests, flow of air occured only over

the four sides of the test box, on account of which it is necessary to make a correction to allow for the difference in loss of heat from the ends and the sides. It is assumed that the loss of heat from the ends is the same during the velocity tests as during the still air tests, and the correction is accordingly made in the following manner:

$$H_s = H_t - u S_e (T_1 - T_4)$$

in which,

H_s is the heat loss through the sides, B.t.u.

H_t is the total heat loss from the test box, B.t.u.

u is the unit transmission of the test box, obtained from the still air tests.

S_e is the mean area of the ends of the box, sq. ft.

T_1 is the inside air temperature, deg. Fahr.

T_4 is the outside air temperature, deg. Fahr.

In determining the coefficients for the air velocity tests, the relations given on page 30 are used; H_s is substituted for the heat loss, and the respective areas of the sides instead of those of the entire box.

In making a traverse to determine the quantity of air flowing, the duct was divided into five concentric zones of equal area and readings taken on the circle which equally divides the area of each zone. The traverse was made across on one diameter only, thus giving ten readings in inches of water, which will be called h. To calculate the mean velocity these values of h were substituted in the following equation:

$$V_m = \frac{18.27}{d^{1/2}} \left[\frac{(\sqrt{h_1} + \sqrt{h_2} + \sqrt{h_3} + etc.)}{n} \right]$$

in which,

V_m is the mean velocity in feet per second.

d is the density of the air.

h is the velocity pressure in inches of water.

n is the number of readings taken.

Knowing the mean velocity of the air in the duct and the relative areas of the duct and the space between the test column and the surrounding hood, the air velocity over the surface of the test column can readily be determined.

The space between the hood and the test column was changed in going from the low to the high velocity tests in order to carry the velocities as high as desired.

III. RESULTS

The results of the Heat Transmission Tests are given on the following pages. In most cases there are two separate sets of tests for each material, the first being the mercury thermometer tests, and the second those in which the thermocouples were used. For every thermometer test there is a thermocouple test which corresponds to it, the two having been run at the same time.

Coefficients of Heat Transmission. In each case, u is the heat lost from one sq. ft. of wall surface, per hour, per degree difference in air temperature, inside to outside, for the thickness of wall actually tested. For the solid walls, such as the brick, concrete, cork, etc., C is the heat lost from one sq. ft. of wall surface, per hour, per degree difference in the surface temperatures, per inch in thickness of of the material tested. For walls made of other than solid materials, such as the tile walls, the value of C is given for the thickness of wall actually tested. K_1 is the heat lost from one sq. ft. of wall surface, per hour, per degree difference in temperature between the inside air and inside wall surface. K_2 is the heat lost from one sq. ft. of wall surface per hour, per degree difference in temperature between the outside wall surface and the outside air. Thickness or nature of the wall, that is solid or otherwise, has nothing to do with determining the surface coefficients.

HEAT TRANSMISSION TESTS

Material	Density	Thickness	Areas: Mean	Areas: Inside	Areas: Outside	Test	Heat Loss per Hour B.T.U.	Temperature: Air	Temperature: Wall	Differences: Air to Wall	Differences: Wall to Air	Coefficients: μ	C	K_1	K_2
2-in. Tile ½-in. Cement Plaster on Both Sides	119.3 Lb./Cu. Ft.	2.02"	46.16 Sq. Ft.	36.06 Sq. Ft.	56.26 Sq. Ft.	Thermometer	1744.5	77.57	19.18	28.08	30.31	0.49	1.97	1.72	1.02
							1039.0	55.41	12.41	23.02	19.98	0.41	1.81	1.25	0.93
							690.3	32.93	7.26	13.87	11.71	0.45	2.06	1.38	1.05
						Th-Couple	1744.5	84.69	38.05	14.95	31.69	0.45	0.99	3.24	0.98
							1039.0	57.38	26.75	10.25	21.88	0.39	0.84	2.81	0.85
							690.3	35.99	14.65	8.80	11.29	0.42	1.02	2.18	1.09
4-in. Tile ½-in. Cement Plaster on Both Sides	127.0 Lb./Cu. Ft.	3.84"	44.33 Sq. Ft.	24.28 Sq. Ft.	64.39 Sq. Ft	Thermometer	1133.5	57.74	20.07	24.31	13.36	0.44	1.27	1.92	1.32
							687.7	41.08	14.94	14.72	11.42	0.38	1.04	1.92	0.94
							400.5	25.11	8.05	9.94	7.12	0.36	1.12	1.66	0.87
						Th-Couple	1133.5	59.78	43.30	3.65	12.83	0.43	0.59	12.80	1.37
							687.7	45.12	25.65	7.85	11.62	0.34	0.61	3.61	0.92
							400.5	29.19	13.60	8.15	7.44	0.31	0.67	2.02	0.84
6-in. Tile ½-in. Cement Plaster on Both Sides	124.3 Lb./Cu. Ft.	6.77"	57.61 Sq. Ft.	31.11 Sq. Ft.	84.12 Sq. Ft	Thermometer	1243.5	64.29	24.71	24.67	14.91	0.34	0.87	1.62	0.99
							798.5	39.49	14.54	16.79	8.16	0.35	0.95	1.53	1.16
							519.5	23.37	8.33	11.03	4.09	0.39	1.08	1.51	1.51
						Th-Couple	1243.5	68.30	46.24	6.06	16.00	0.32	0.47	6.60	0.92
							798.5	39.54	28.00	2.93	8.61	0.35	0.50	8.76	1.10
							519.5	24.07	17.56	1.90	4.61	0.38	0.51	8.79	1.34

Heat Transmission Tests

Material	Density	Thickness	Areas: Mean	Areas: Inside	Areas: Outside	Test	Heat Loss per Hour B.T.U.	Temperature Differences: Air	Wall	Air to Wall	Wall to Air	Coefficients: μ	C	K_1	K_2
2-Course Brick	131.9#/Cu.Ft.	8.77"	72.08 Sq.Ft.	39.35 Sq.Ft.	104.80 Sq.Ft.	Thermometer	1548.0	78.89	33.21	30.54	15.14	2.39	5.67	1.29	0.98
							1231.5	61.10	25.09	26.41	9.60	2.45	5.97	1.18	1.22
							858.7	35.65	12.08	19.08	4.49	2.93	8.64	1.14	1.82
						Th-Couple	1548.0	77.92	47.93		16.89	2.42	3.93	3.00	1.13
							1231.5	60.39	36.59		8.40	2.48	4.09	2.03	1.40
							858.7	35.10	20.58	9.80	4.72	2.98	5.08	2.23	1.73
3-In. Concrete 1-2-4 Mixture	139.7#/Cu.Ft.	3.19"	33.76 Sq.Ft.	23.58 Sq.Ft.	43.94 Sq.Ft.	Thermometer	2088.0	78.27	18.47	26.39	33.41	2.52	10.68	3.36	1.42
							1527.5	57.81	12.59	22.66	22.58	2.45	11.46	2.86	1.54
							1066.0	40.14	8.81	16.44	14.89	2.51	11.44	2.75	1.63
						Th-Couple	2088.0	80.95	23.77	20.83	36.35	2.45	8.31	4.25	1.31
							1527.5	58.97	16.52	18.36	23.99	2.44	8.74	3.53	1.45
							1066.0	39.61	12.77	12.23	14.61	2.54	7.89	3.70	1.66
3-In. Concrete Roofing Covered	Concrete 139.7#/Cu.Ft. Roofing 1.34#/Sq.Ft. Gravel 0.83#/Sq.Ft.	3.34"	35.03 Sq.Ft.	23.58 Sq.Ft.	46.47 Sq.Ft.	Thermometer	1261.5	65.33	22.74	19.19	13.40	0.55	1.58	2.79	2.03
							690.0	31.25	8.42	13.17	9.66	0.63	2.34	2.22	1.54
							356.3	17.60	4.11	7.15	6.34	0.58	2.48	2.11	1.21
						Th-Couple	1261.5	64.64	27.15	14.30	13.19	0.56	1.33	3.74	2.06
							690.0	28.55	10.68	8.17	9.70	0.69	1.84	3.58	1.53
							356.3	17.07	3.88	5.84	7.35	0.60	2.62	2.59	1.04

HEAT TRANSMISSION TESTS

Material	Density	Thickness	Areas: Mean	Areas: Inside	Areas: Outside	Test	Heat Loss per Hour B.T.U.	Temperature Differences: Air	Wall	Air to Wall	Wall to Air	Coefficients: μ	C	K_1	K_2
1-in. Wood (Fir)	33.37# / Cu.Ft.	1.06	51.04 Sq. Ft.	46.94 Sq. Ft.	55.14 Sq. Ft.	Thermometer	1602.5	72.48	24.62	27.24	20.62	0.46	1.35	1.25	1.41
							1041.0	49.20	16.49	18.44	14.27	0.44	1.31	1.20	1.32
							466.5	22.74	6.84	9.16	6.74	0.43	1.42	1.08	1.26
						Th-Couple	1602.5	70.15	33.03	16.80	20.32	0.47	1.01	2.03	1.43
							1041.0	48.20	24.37	9.93	13.90	0.45	0.89	2.23	1.36
							466.5	20.92	10.80	3.73	6.39	0.46	0.90	2.66	1.33
2-in. Corkboard (Nonpareil)	9.74# / Cu. Ft.	2.03"	39.34 Sq. Ft.	31.72 Sq. Ft.	46.96 Sq. Ft.	Thermometer	368.2	66.27	48.59	10.52	7.16	0.29	0.39	1.10	1.09
							213.3	41.83	30.10	7.06	4.67	0.26	0.37	0.95	0.98
							144.9	28.51	20.57	5.16	2.78	0.26	0.36	0.89	1.11
						Th-Couple	368.2	70.94	58.90	5.67	6.37	0.27	0.32	2.05	1.23
							213.3	44.85	36.80	3.87	4.18	0.25	0.30	1.74	1.09
							144.9	30.72	25.67	2.86	2.19	0.24	0.29	1.60	1.41
1½-in. Magnesia Board	13.5# / Cu. Ft.	1.55"	50.69 Sq. Ft.	45.13 Sq. Ft.	56.26 Sq. Ft.	Thermometer	1031.3	84.70	44.36	26.71	13.63	0.37	0.71	0.86	1.35
							754.2	63.48	30.89	22.21	10.38	0.36	0.75	0.76	1.29
							495.9	41.55	20.77	14.07	6.71	0.37	0.73	0.78	1.31
						Th-Couple	1031.3	82.55	62.20	7.80	12.55	0.38	0.51	2.93	1.46
							754.2	61.96	45.80	6.37	9.79	0.37	0.50	2.66	1.37
							495.9	40.16	29.06	4.30	6.80	0.38	0.52	2.55	1.30

HEAT TRANSMISSION TESTS

Material	Density	Thickness	Areas: Mean	Areas: Inside	Areas: Outside	Test	Heat Loss per Hour B.T.U.	Temperature Differences: Air	Wall	Air to Wall	Wall to Air	Coefficients: μ	C	K_1	K_2
1-IN. ASBESTOS BOARD (CORRUGATED INTERIOR)	20.42#/CU. FT.	1.00"	50.10 SQ. FT.	46.58 SQ. FT.	53.61 SQ. FT.	THERMOMETER	1248.0	73.72	32.13	25.80	15.79	0.34	0.78	1.04	1.47
							796.0	51.28	23.17	17.82	10.29	0.31	0.69	0.96	1.44
							496.2	32.10	12.91	12.15	7.04	0.31	0.77	0.88	1.32
						TH-COUPLE	1248.0	71.16	51.57	5.10	14.49	0.35	0.48	5.26	1.61
							796.0	50.53	36.96	3.34	10.23	0.32	0.43	5.12	1.45
							496.2	31.07	22.10	2.17	6.80	0.32	0.45	4.91	1.36
SHEET ASBESTOS 60 SHEETS 1/64-IN. THICK	48.25#/CU. FT.	1.1"	50.96 SQ. FT.	48.75 SQ. FT.	53.16 SQ. FT	THERMOMETER	856.2	77.33	35.12	31.23	10.98	0.24	0.53	0.56	1.47
							619.7	56.41	24.40	23.15	8.86	0.24	0.55	0.55	1.32
							371.9	32.93	13.46	14.57	4.90	0.24	0.60	0.52	1.43
						TH-COUPLE	856.2	78.43	63.00	4.00	11.43	0.24	0.29	4.39	1.41
							619.7	57.10	44.60	3.53	8.97	0.23	0.27	3.57	1.30
							371.9	33.05	25.97	1.86	5.22	0.24	0.31	4.10	1.34
SINGLE STRENGTH GLASS 76.3% GLASS	141.1#/CU. FT.	0.085	43.23 SQ. FT	42.93 SQ. FT	43.53 SQ. FT	TH-COUPLE	2240.5	67.64	6.00	27.67	33.97	1.00	0.96	2.44	1.99
							1500.0	48.02	2.57	20.10	25.35	0.95	1.51	2.25	1.78
							832.5	32.20	2.22	14.56	15.42	0.78	0.97	1.72	1.63
2 PANES GLASS 1/2" AIR SPACE 69.3% GLASS	141.1#/CU. FT.	0.085" & 0.127"	45.46 SQ. FT.	42.93 SQ. FT.	47.98 SQ. FT	TH-COUPLE	1636.5	75.11	34.57	14.97	25.57	0.69	1.50	3.68	1.93
							1104.0	54.43	24.53	13.57	16.33	0.64	1.43	2.73	2.03
							731.5	38.09	17.10	9.70	11.29	0.61	1.36	2.54	1.95

HEAT TRANSMISSION TESTS

MATERIAL	DENSITY	THICKNESS	AREAS			TEST	HEAT LOSS PER HOUR B.T.U.	TEMPERATURE DIFFERENCES				COEFFICIENTS			
			MEAN	INSIDE	OUTSIDE			AIR	WALL	AIR TO WALL	WALL TO AIR	μ	C	K_1	K_2
BRICK ONE COURSE	131.9#/CU.FT.	3.79"	25.78 SQ.FT.	17.48 SQ.FT.	34.08 SQ.FT.	TH-COUPLE	1033.0	77.71	38.15	16.35	23.21	1.96	3.98	3.61	1.31
							688.7	60.15	27.15	13.80	19.20	1.68	3.73	2.85	1.05
							303.7	26.14	9.80	9.65	6.69	1.71	4.55	1.80	1.33
GLASS SINGLE PANE 91.4 % GLASS	141.1#/CU.FT.	0.085"	10.14 SQ.FT.	10.02 SQ.FT.	10.25 SQ.FT.	TH-COUPLE	751.2	72.85	3.05	29.00	40.80	1.11	2.26	2.83	1.97
							444.0	48.27	2.65	19.55	26.07	0.99	1.53	2.48	1.82
							147.1	19.35	1.65	7.95	9.75	0.82	0.82	2.02	1.62
2-IN. TILE ½-IN. PLASTER (BOTH SIDES) OUTSIDE-ROOFING COVERED	TILE 119.86#/CU.FT. ROOFING 1.34#/SQ.FT. GRAVEL 0.83#/SQ.FT	TILE 2.02" ROOFING 0.15"	47.61 SQ.FT.	36.06 SQ.FT	59.15 SQ.FT.	THERMOMETER	1942.0	87.71	28.29	35.43	23.99	0.47	1.44	1.52	1.37
							1486.5	66.04	20.45	28.53	17.06	0.47	1.53	1.45	1.47
							1039.0	45.53	13.75	19.92	11.86	0.48	1.59	1.45	1.48
						TH-COUPLE	1942.0	83.39	48.55	11.70	28.14	0.49	0.84	4.60	1.17
							1486.5	69.07	38.32	11.95	18.80	0.45	0.82	3.45	1.34
							1039.0	51.13	26.67	10.65	13.81	0.43	0.82	2.71	1.27

The values of the transmission coefficients, u, are of little significance, on account of the abnormally high values of the inside surface coefficients, K_1. The radiation from the heating coil to the inside wall of the test column was apparently high enough so that it raised the inside surface coefficient above the outside one. It was thought that with this method of heating, that is eliminating the fan on the inside of the box, that surface coefficients corresponding to approximately still air conditions would be obtained for both the inside and outside surfaces. In which case, the transmission would have been that corresponding to still air conditions.

It will be noted from the result sheets that the K_2 values of each set of tests roughly check each other, which indicates that mercury thermometers imbedded half-way in the material give fairly close readings of the outside surface temperatures. The values of the transmission coefficients, u, show that for the air to air coefficient mercury thermometers give fairly accurate results. However, for the inside surface temperatures, where oil wells imbedded in the surface were used, the results from the mercury thermometer tests are far from correct. Thus there is no checking of the K_1 and C values of the two sets of tests.

Fortunately, for calculating heat transmission coefficients of simple or compound walls it is only necessary to have the coefficients of conductivity and those of the surfaces of the materials of which the wall is composed. Consequently, in selecting the coefficients for the following table only the outside surface coefficients were considered in getting

Coefficients Based on Heat Transmission Tests

Material	C	K
1. Brick	4.00	1.40
2. Concrete 1–2–4 Mixture	8.30	1.30
3. Wood (Fir - One surface Finished)	1.00	1.40
4. Corkboard	0.32	1.25
5. Magnesia Board	0.50	1.45
6. Glass	2.06	2.00
7. 2-in. Tile, ½" Plaster on Both Surfaces	1.00	1.10
8. 4-in. Tile, ½" Plaster on Both Surfaces	0.60	1.10
9. 6-in. Tile, ½" Plaster on Both Surfaces	0.47	1.10
10. 2-in. Tile, Plastered as Above, & Roofing Covered	0.84	1.25
11. Asbestos Board	0.50	1.60
12. Sheet Asbestos	0.30	1.40
13. Double Glass, ½" Air Space	1.50	2.00
14. Roofing	5.30 *	1.25
15. Air Space	1.00 – 1.70 †	—

* Calculated from Values of C for 2" Tile With and Without Roofing.

† See "Air Spaces"

the values found under the column headed, K. These values are the surface coefficients for still air conditions, and are the B.t.u. loss from one sq. ft. of surface, per hour, per degree difference between the surface temperature and the temperature of the air in contact with it. Values of C are the B.t.u. loss from one sq. ft. of surface, per hour, per degree difference between the surface temperatures, per inch in thickness for solid walls, and for the actual thickness for other than solid walls. In selecting these coefficients most weight has been given to the values obtained from the tests of greatest air temperature differences, and only the tests where thermocouples were used were considered.

Attention is called to the value of C for roofing, deduced from the values of C from the 2-inch tile tests with and without the roofing. This was calculated from the relation:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

In the table of coefficients will be found values for the so-called conductivity of air spaces, an explanation of which will be found under the article on Air Spaces.

Effect of Air Velocity on Surface Coefficients. Results of the Air Velocity Tests on Brick are given on page 42.

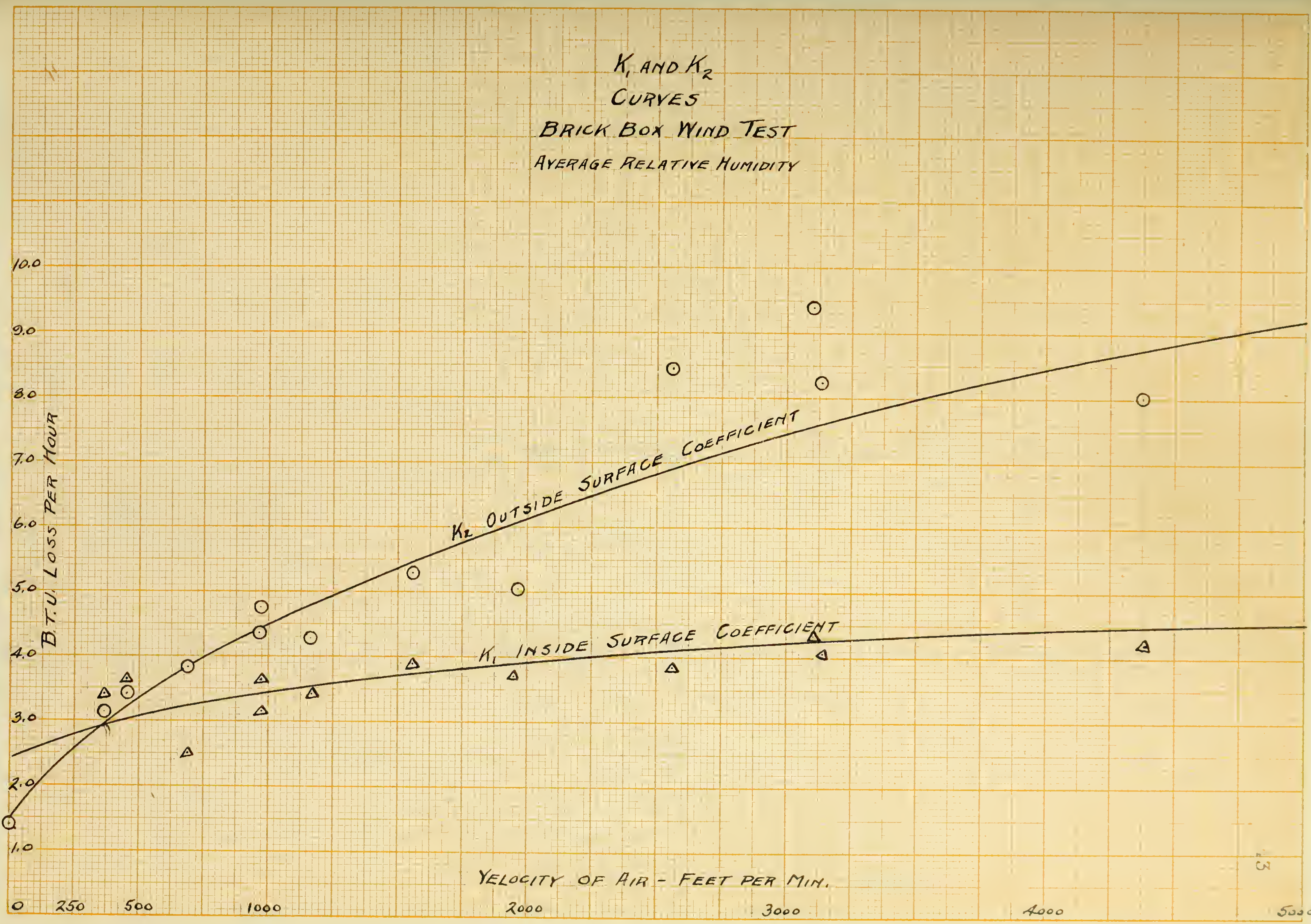
Curves showing the effect of velocity of air on the various coefficients for a 4-inch Brick wall are given on pages 43 and 44. Just why the K_1 curve should increase with an increasing air velocity over the outside of the box is difficult to explain. Air moving over the outside surface causes the outside surface temperature to approach that of the outside air, with an increase in velocity. The loss of heat

Air Velocity Tests

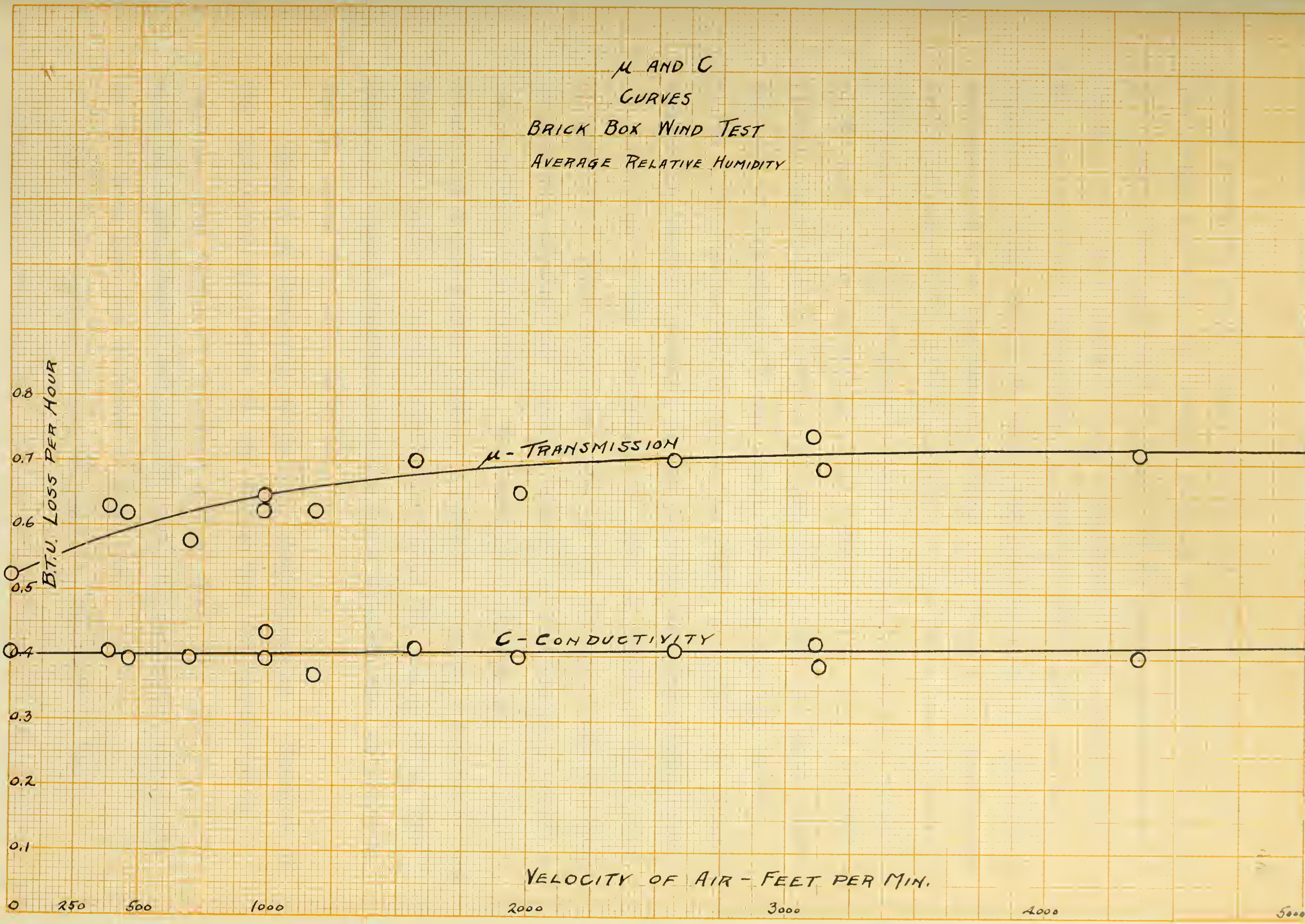
Brick

Partly Saturated Air

No.	Total Heat Loss	Corrected Heat Loss	Air Temperature Difference	Wall Temperature Difference	Air To Wall Difference	Wall To Air Difference	μ	C	K_1	K_2	Air Velocity	Humidity
1	1278.0	1117.2	73.96	47.40	19.05	7.51	0.70	4.15	3.89	5.30	1563	–
2	1227.5	1061.0	76.55	49.15	19.45	7.95	0.64	3.98	3.63	4.76	985	80.0
3	1126.5	967.2	73.25	45.55	17.80	9.90	0.61	3.91	3.61	3.48	461	43.5
4	1175.5	1019.3	71.81	46.70	17.95	7.16	0.66	4.02	3.77	5.07	1955	50.5
5	1413.0	1244.2	77.65	53.95	18.95	4.72	0.74	4.25	4.36	9.40	3100	50.0
6	1434.5	1241.5	80.73	56.00	19.25	5.48	0.71	4.09	4.29	8.08	4378	–
7	1485.0	1317.0	77.23	55.60	16.40	5.23	0.79	4.37	5.34	9.19	5200	71.0
8	1191.0	1039.5	69.54	48.55	16.50	4.49	0.69	3.95	4.19	8.26	3135	51.0
9	1171.5	1024.4	67.66	45.95	17.40	4.31	0.70	4.11	3.91	8.47	2570	61.0
10	1147.0	991.4	73.30	42.70	19.40	11.20	0.63	4.08	3.40	3.15	373	49.5
11	1144.5	977.0	78.90	43.95	25.90	9.05	0.57	3.91	2.51	3.84	701	35.0
12	1150.0	992.5	74.15	45.00	21.00	8.15	0.62	3.88	3.14	4.34	985	44.0
13	1148.0	991.5	73.70	46.55	19.35	7.50	0.62	3.75	3.40	4.71	1175	32.0
					Saturated Air							
1	1141.5	980.0	74.35	47.35	18.60	8.40	0.61	3.64	3.50	4.15	882	95.0
2	1147.0	989.0	72.75	46.00	17.45	9.30	0.63	3.78	3.77	3.79	698	98.0
3	1149.5	989.1	73.80	47.50	19.10	7.20	0.62	3.66	3.44	4.89	1338	92.0
4	1148.0	979.9	77.40	50.50	14.75	12.15	0.59	3.41	4.42	2.88	472	99.5



K1 AND K2
CURVES
BRICK BOX WIND TEST
AVERAGE RELATIVE HUMIDITY
K2 OUTSIDE SURFACE COEFFICIENT
K1 INSIDE SURFACE COEFFICIENT
B.T.U. LOSS PER HOUR
VELOCITY OF AIR - FEET PER MIN.
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
250
500
1000
2000
3000
4000
5000


μ AND C
CURVES
BRICK BOX WIND TEST
AVERAGE RELATIVE HUMIDITY
μ - TRANSMISSION
C - CONDUCTIVITY
B.T.U. LOSS PER HOUR
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
250
500
1000
2000
3000
4000
5000
VELOCITY OF AIR - FEET PER MIN.

being practically the same, in all but a few of the tests, the temperature of the inside surface would have to drop until the temperature gradient through the material was the same as in the still air tests. Then on account of the lowering of the inside wall temperature, a drop of the inside air temperature of such magnitude that the coefficient for the inside surface would be the same as found under still air conditions would be expected. But according to the tests the temperature difference is less than this amount resulting in an increase of K_1 with velocity of air. The conductivity curve is practically horizontal as would be expected, since the mean temperature of the material was about the same for all of the tests. The transmission curve increases with the air velocity similarly to the increase of the outside surface coefficient.

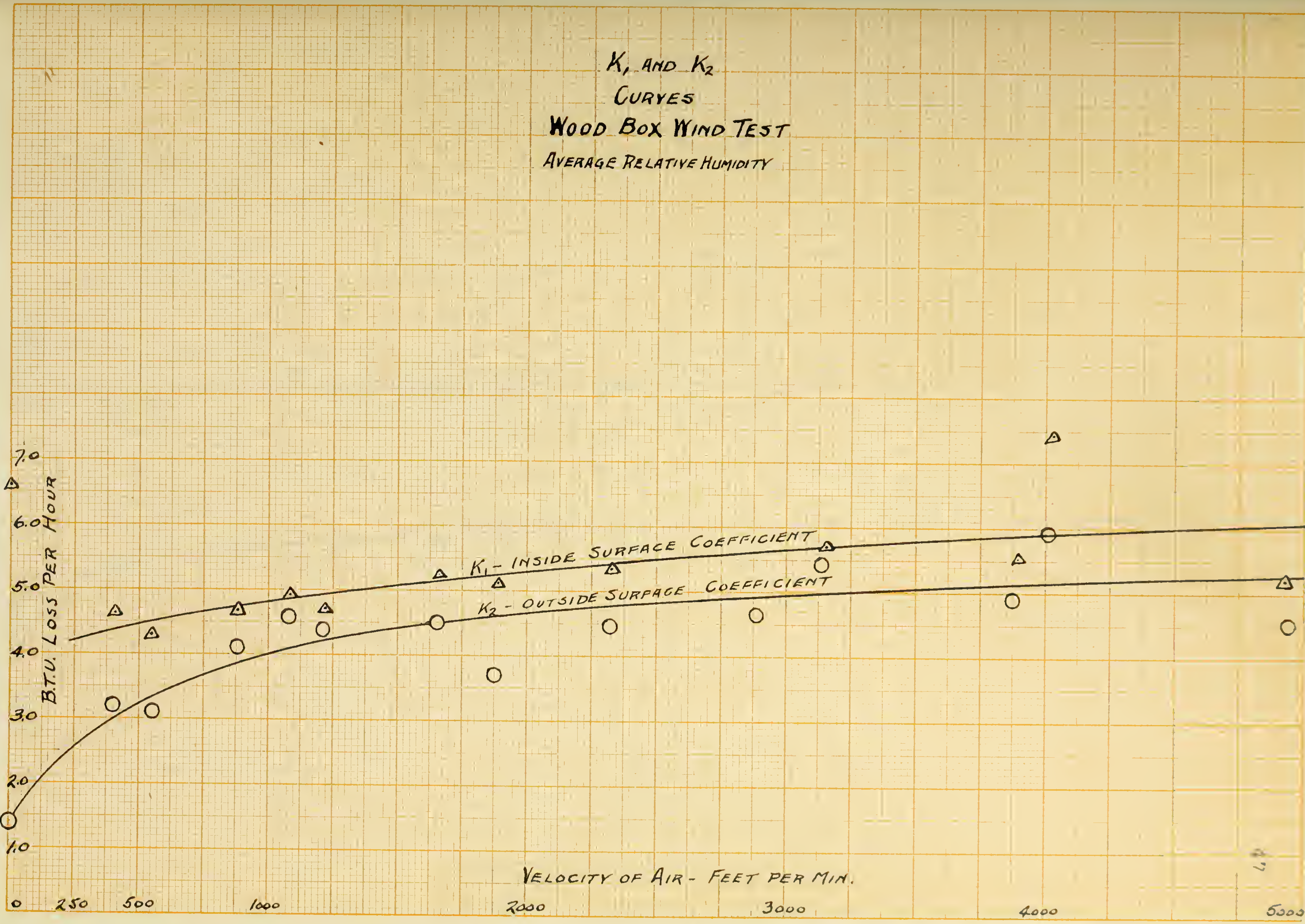
Results of the Air Velocity Tests on Wood are tabulated on page 46. These data are plotted on the curve sheets, pages 47 and 48, showing the rate of change of the various coefficients with air velocity. The remarks regarding K_1 for the Brick Box Tests apply equally as well to the K_1 values for the Wood Box Tests. In the still air tests the value of K_1 for Wood is evidently wrong, and has been disregarded in drawing the K_1 curve for this material.

Effect of Humidity on Surface Coefficients. Results of the saturated air tests on the Brick Box are tabulated on page 42, and those on the Wood Box on page 49. Curves of the various coefficients determined from the saturated air tests on the Wood Box are plotted on page 50.

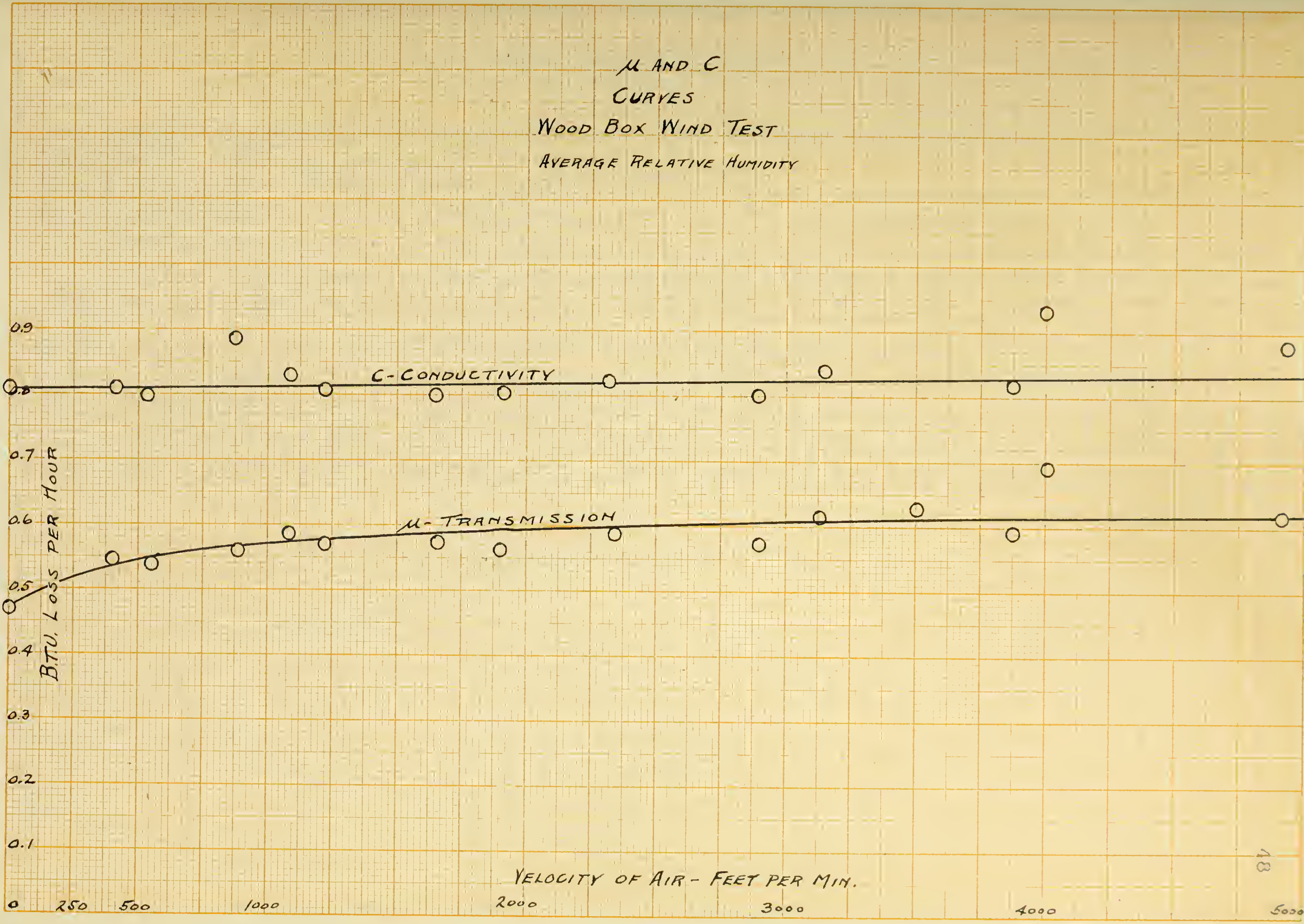
The three curves shown on page 51, taken from the u

Air Velocity Tests
Wood
Partly Saturated Air

No.	Total Heat Loss	Corrected Heat Loss	Air Temperature Difference	Wall Temperature Difference	Air To Wall Difference	Wall To Air Difference	μ	C	K_1	K_2	Air Velocity	Humidity
1	1369.5	1176.5	79.58	60.40	9.45	9.73	0.59	0.82	5.37	4.47	2322	53.5
2	1401.5	1212.2	78.05	60.65	9.10	8.30	0.62	0.84	5.75	5.40	3138	61.0
3	1619.0	1422.3	81.08	64.00	8.20	8.88	0.70	0.94	7.44	5.92	4015	45.0
4	1452.0	1250.7	83.02	63.05	9.10	10.87	0.60	0.84	5.93	4.25	5665	79.5
5	1405.5	1212.8	79.44	60.95	8.25	10.24	0.61	0.85	6.35	4.38		77.0
6	1379.0	1186.7	79.25	61.00	9.25	9.00	0.60	0.82	5.54	4.87	3875	81.0
7	1283.0	1098.8	75.82	57.95	9.10	8.77	0.58	0.80	5.21	4.63	2889	78.5
8	1341.5	1144.6	81.18	60.20	9.55	11.43	0.56	0.80	5.16	3.70	1905	87.5
9	1321.0	1143.1	73.33	54.25	9.75	9.33	0.62	0.89	5.16	4.53	4925	77.0
10	1237.0	1058.1	73.76	56.35	8.70	8.71	0.57	0.79	5.25	4.49	1668	70.0
11	1314.0	1139.0	77.14	58.15	9.85	9.14	0.59	0.83	4.99	4.60	1083	79.0
12	1238.0	1058.7	73.95	55.40	9.65	8.90	0.57	0.81	4.74	4.40	1236	72.5
13	1258.5	1072.5	76.65	57.20	9.80	9.65	0.56	0.79	4.72	4.12	882	71.5
14	1320.0	1120.0	82.43	59.40	11.00	13.03	0.54	0.79	4.39	3.17	548	68.5
15	1348.5	1145.4	83.77	60.05	10.55	13.17	0.54	0.81	4.69	3.21	410	—



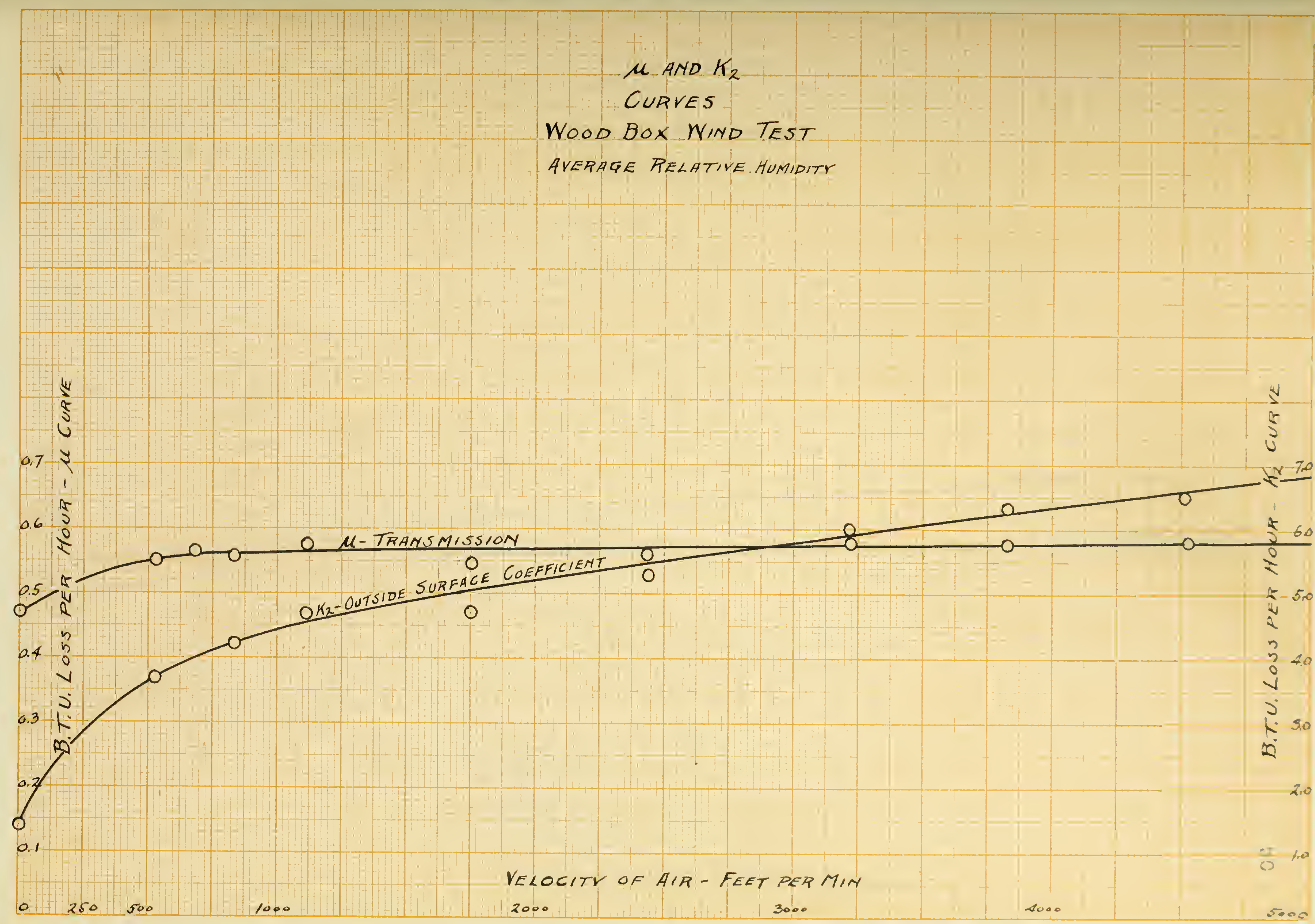
K, AND K2
CURVES
WOOD BOX WIND TEST
AVERAGE RELATIVE HUMIDITY
K1 - INSIDE SURFACE COEFFICIENT
K2 - OUTSIDE SURFACE COEFFICIENT
B.T.U. LOSS PER HOUR
7.0
6.0
5.0
4.0
3.0
2.0
1.0
VELOCITY OF AIR - FEET PER MIN.
0
250
500
1000
2000
3000
4000
5000
47



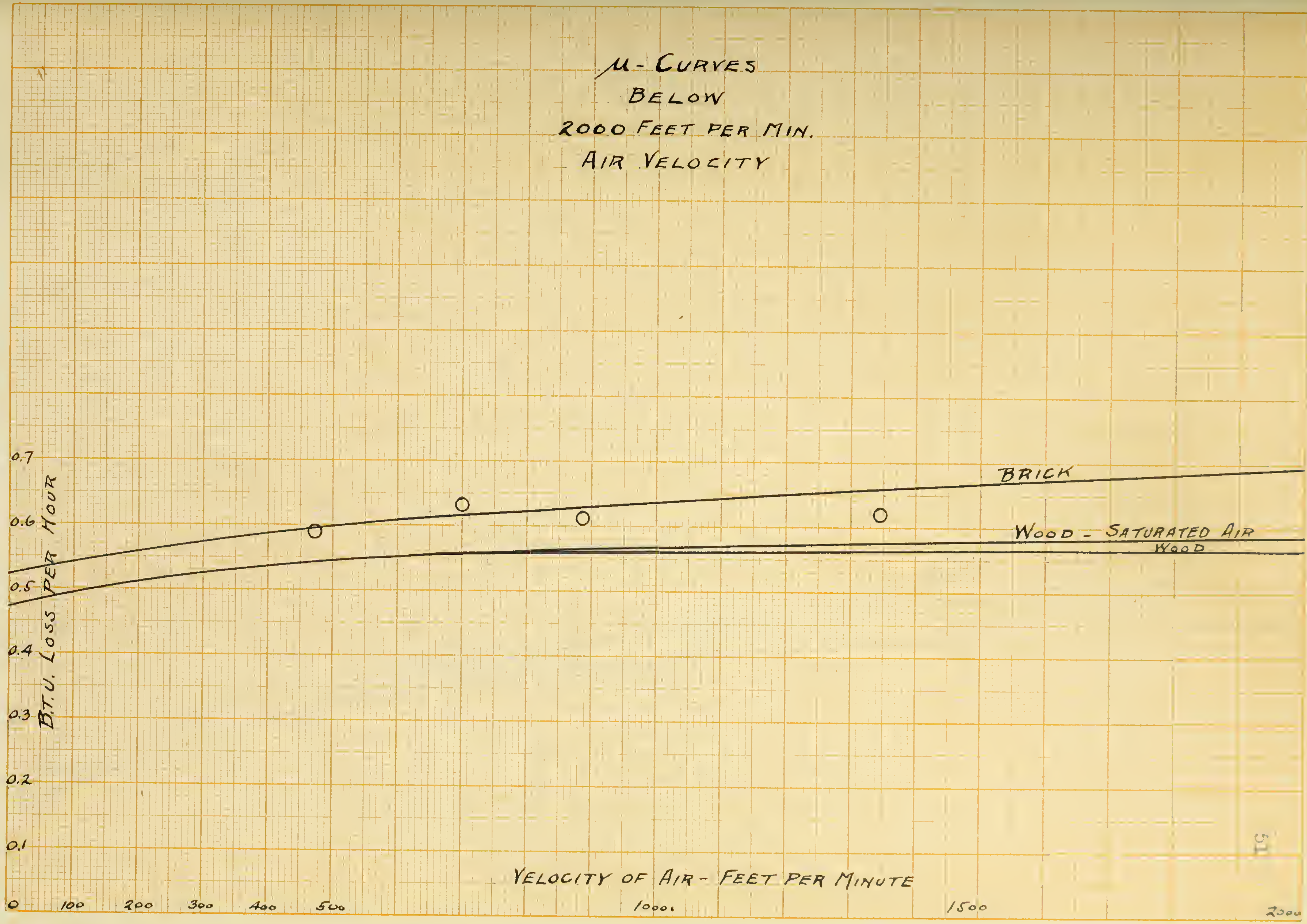
μ AND C
CURVES
WOOD BOX WIND TEST
AVERAGE RELATIVE HUMIDITY
C-CONDUCTIVITY
μ-TRANSMISSION
B.T.U. LOSS PER HOUR
VELOCITY OF AIR - FEET PER MIN.
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
250
500
1000
2000
3000
4000
5000

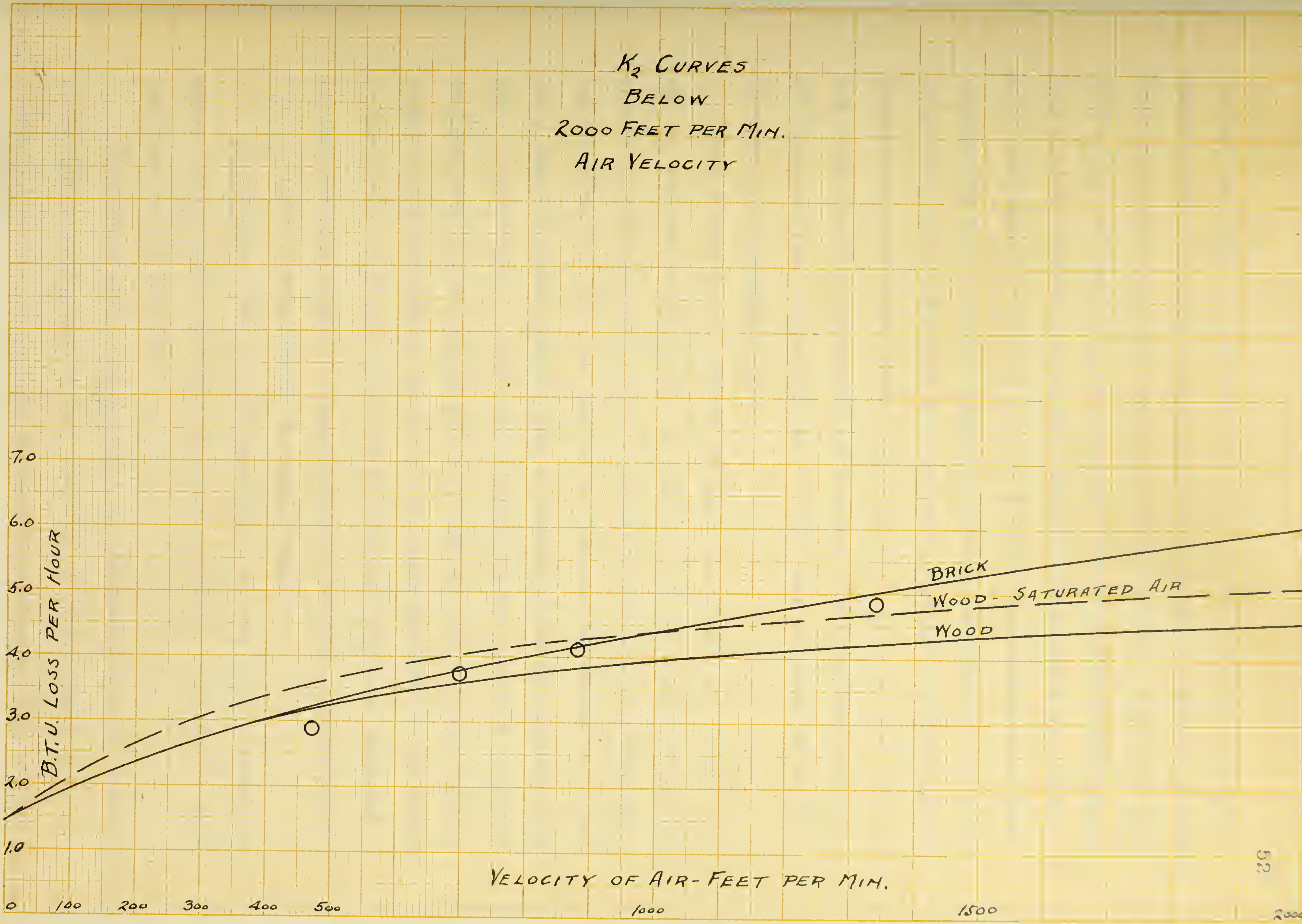
Air Velocity Tests
Wood
Saturated Air

No.	Total Heat Loss	Corrected Heat Loss	Air Temperature Difference	Wall Temperature Difference	Air To Wall Difference	Wall To Air Difference	μ	C	K_1	K_2	Air Velocity	Humidity
1	1420.5	1208.8	87.23	63.80	11.40	12.03	0.55	0.80	4.57	3.71	528	98.0
2	1405.0	1200.2	84.40	62.80	11.70	9.90	0.57	0.81	4.43	4.48	678	98.5
3	1457.0	1243.0	88.26	65.80	11.60	10.86	0.56	0.80	4.63	4.23	837	98.5
4	1465.0	1255.3	86.42	64.45	11.10	9.87	0.58	0.82	4.88	4.70	1108	98.0
5	1239.0	1052.0	77.15	47.55	21.30	8.30	0.54	0.93	2.13	4.69	1763	99.8
6	1275.0	1093.0	75.20	49.45	18.95	6.80	0.58	0.93	2.49	5.94	3210	98.0
7	1275.5	1087.6	77.25	51.30	18.35	7.60	0.56	0.89	2.56	5.29	2438	98.0
8	1275.5	1093.2	75.15	50.00	18.75	6.40	0.58	0.92	2.52	6.31	3795	97.5
9	1277.0	1096.2	74.55	49.80	18.55	6.20	0.59	0.93	2.55	6.53	4510	86.0



μ AND K2
CURVES
WOOD BOX WIND TEST
AVERAGE RELATIVE HUMIDITY
μ - TRANSMISSION
K2 - OUTSIDE SURFACE COEFFICIENT
B.T.U. LOSS PER HOUR - μ CURVE
B.T.U. LOSS PER HOUR - K2 CURVE
VELOCITY OF AIR - FEET PER MIN
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0
250
500
1000
2000
3000
4000
5000


μ - CURVES
BELOW
2000 FEET PER MIN.
AIR VELOCITY
BRICK
WOOD - SATURATED AIR
WOOD
B.T.U. LOSS PER HOUR
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
1000
1500
2000
VELOCITY OF AIR - FEET PER MINUTE


K_2 CURVES
BELOW
2000 FEET PER MIN.
AIR VELOCITY
BRICK
WOOD - SATURATED AIR
WOOD
B.T.U. LOSS PER HOUR
VELOCITY OF AIR - FEET PER MIN.
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
100
200
300
400
500
1000
1500
2000

curves on pages 44, 48 and 50, at the lower velocities, together with the four points plotted, which are points obtained from the saturated air tests on the Brick Box, page 42, show the effect of humidity on the heat transmission coefficient. The plotted points lie close enough to the curve for Brick with partially saturated air to justify the conclusion that increasing the relative humidity from an average of 51.6% to an average of 95.9% does not increase the heat transmission through a brick wall four inches thick. Also in the case of the wood box the effect of increasing the relative humidity of the air from an average of 71.3% to an average of 96.9% is practically negligible.

The three curves shown on page 52, which are taken from the K_2 curves on pages 43, 47 and 50, at the lower velocities, together with the four points plotted, which are points obtained from the data of the saturated air tests on the Brick Box, page 42, show the effect of humidity on the outside surface coefficients. Here the conclusion is that the increase in humidity has no appreciable effect on the outside surface coefficient for Brick, while in the case of Wood an increase is apparent, the practical importance of which is doubtful, as the increase would be negligible in making a calculation for the heat transmission through a wall.

Air Spaces. Heat is transferred across an air space by means of all three methods of heat transfer, radiation, convection and conduction.

Obviously with a large drop in temperature across the air space the circulation of the air will be more rapid and

convection loss will therefore be greater than with a small drop. Removing the air from the space has no appreciable effect until very high vacuums are reached, as Nusselt found that a 29.96-inch vacuum (referred to a 30-inch barometer) had little effect on the loss by convection. So a very high vacuum is necessary to reduce the loss by convection an appreciable amount. Convection loss then depends on the circulation of the air, which depends on the temperature difference of the two containing walls.

Air is a poor conductor of heat and this accounts for the general belief that air spaces built into walls will reduce the loss of heat to a great extent, no matter what the structure. The double glass box with a half-inch air space in between the panes illustrates the value of an air space in constructions of this nature. A comparison of the brick and tile tests shows favorable results for the air space.

However, when higher temperatures than those met in ordinary wall construction are encountered, the transfer of heat across an air space assumes a different aspect. For the lower temperature differences the radiation factor is not of very great importance. But remembering that the quantity of heat that passes across an air space by means of radiation depends on the fourth power of the absolute temperatures of the surfaces enclosing the air space, it will be seen that the radiation loss will increase rapidly with the temperatures of the two surfaces, although the difference between these surfaces remains constant. While with a solid material, instead of the air space, the heat would be transferred through it by

means of conduction alone. And the amount of heat lost by conduction would increase only slightly with an increase in temperature, if the temperature difference between the two surfaces remained constant.

Thus an air space may be as efficient a heat insulator as a solid insulating material, at the lower temperatures, with the same temperature differences. While with a higher mean temperature and the same temperature differences the air space would prove very inefficient.

Ray and Kreisinger in their bulletin[15] state that the heat passing through furnace walls would be much reduced if the air spaces were filled with brick, or better with some poor conducting materials, such as ash, sand, mineral wool etc. In other words, due to the radiation factor, when heat at low temperatures is to be insulated use air spaces; when the heat is at high temperatures as in the case of furnace walls, use solids of poor conductivity. That the space is less effective at high temperatures is known to makers of "Thermos" bottles who advertize that such bottles keep liquids cold 72 hours and keep liquids hot only 24 hours.

From the results of the single glass and the double glass box tests, the so-called conductivity of the 1/2-inch air space, meaning by so-called conductivity the B.t.u. loss per sq. ft. per hour, per degree difference in the surface temperatures of the two containing walls, is calculated to be 1.77.

Professor L. A. Harding, in a Pennsylvania State College Experiment Station Bulletin, gives a value of 1.66 for the so-

15. The Flow of Heat through Furnace Walls, Bureau of Mines.

called conductivity of air spaces ranging from one to six inches in thickness.

From tests reported in Ice and Refrigeration a value of 1.25 is deduced for a 1-inch air space.[16]

From tests on a mail car side, reported by Professor A. C. Willard, a value of 1.59 is deduced for a four-inch air space.[17] Nusselt states that air spaces greater than 3/4-inch in thickness give no additional value for heat insulating purposes, which is substantiated by the above data.

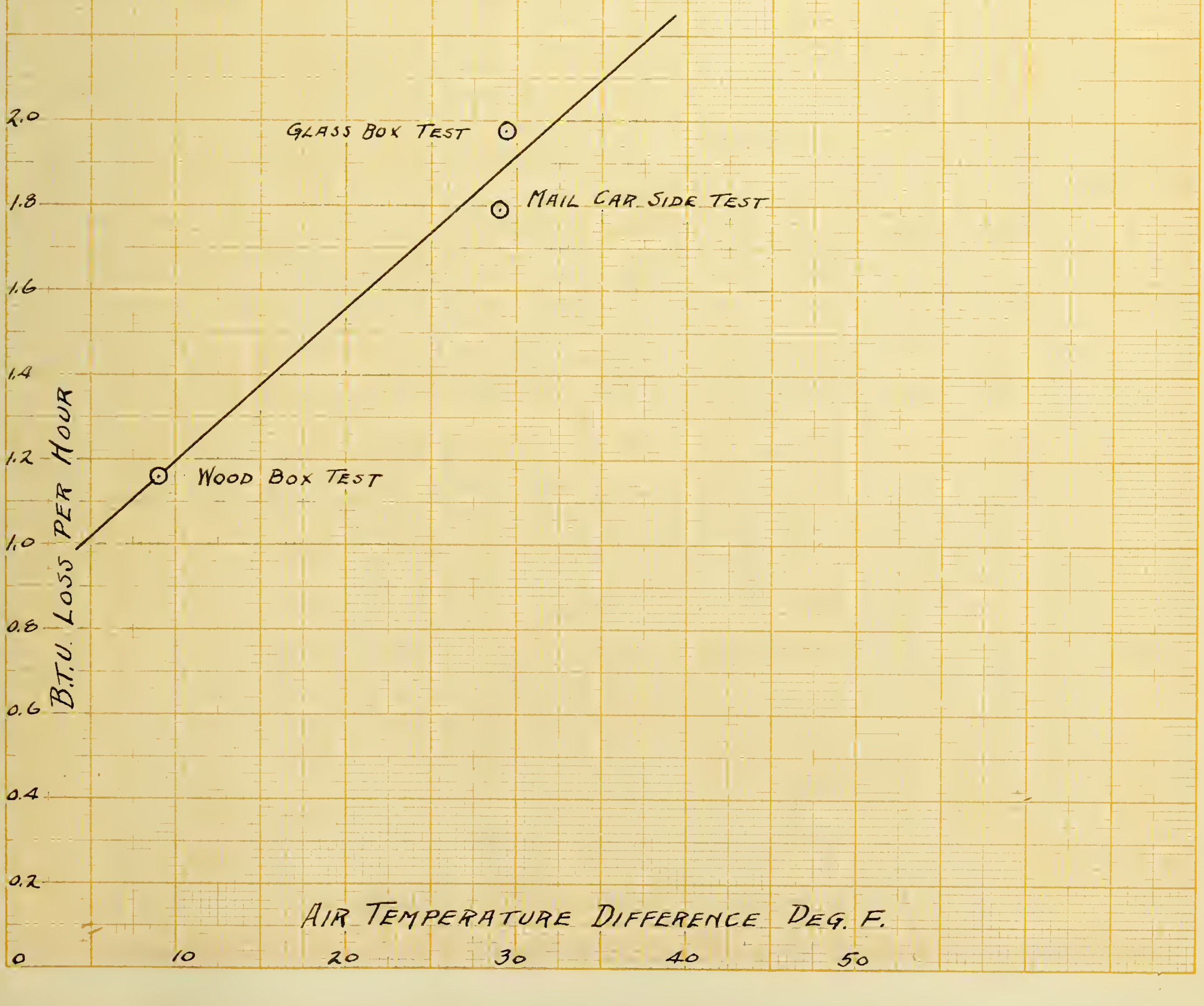
An average of the above values gives a value of 1.57 for the so-called conductivity of an air space.

From the data given above, the temperature drop across the air space was calculated and a curve plotted using air temperature differences as abscissae and the so-called conductivity of air spaces as ordinates. The curve, showing the variation of the so-called conductivity with the temperature difference across the space, is given on page 57.

In making calculations for heat transmission coefficients of compound walls, an air space may be treated in either of the following ways: The air space may be regarded as a solid insulating material through which the heat passes according to the so-called conductivity idea; or considering the transfer by the three methods, radiation, convection and conduction, the radiation and convection would be classed together as the surface coefficient and the true conductivity of the air neglected. Then for every air space there would be two surface coefficients to be taken into account. If different surfaces

16. Refrigerating World, October 1914.
17. Railway Age Gazette, June, 26, 1914.

So-Called Conductivity
Temperature Difference
Curve
for
Air Space Construction



enclosed the air space different surface coefficients would be used for the two walls.

It has been customary to assume still air conditions inside an air space, and consequently to use the surface coefficients corresponding to this condition, which however does not seem to be the case as higher temperature differences are met with.

IV. APPLICATION

Solid Wall Construction. In a simple or compound wall, without air spaces in the construction, there are two surfaces which enter into the calculations for the heat transmission coefficient. For the inside surface a coefficient corresponding to still air conditions is used. This is obtained from the Table of Coefficients on page 40. For the outside surface a coefficient of three times that corresponding to still air conditions is used, which allows for a wind velocity of practically 15 miles per hour. The conductivities for the materials, of which the wall is composed, are obtained from the Table of Coefficients. Substituting these values in the heat transmission formula the heat loss in B.t.u., per sq. ft., per hour, per degree difference in air temperatures is obtained from which the total loss through the walls of a building for the air temperature difference to be met with is readily obtained.

Air Space Construction. For walls containing an air space or spaces, the accepted method of determining the heat transmission is the same as that for a simple or compound wall with the addition of two times as many surface coefficients as there are air spaces included in the construction. The surface coefficients used are those for still air conditions. However as mentioned before this assumption of still air conditions in an air space is probably not quite exact. To determine the

[illegible]

heat transmission of a wall containing an air space according to the method outlined under Air Space Construction the following tentative solution is adopted. First, the temperature drop across the air space is assumed and the so-called conductivity is determined from the curve on page 57. A calculation for the transmission coefficient is then made and the loss for the air temperature difference determined. Dividing this value by the socalled conductivity used for the air space gives the temperature drop across the air space. This should check the assumed temperature drop if the assumption is correct. If the resulting temperature drop is greater than the assumed one, an assumption of temperature drop larger than the previous one is made and calculations made again, and so on until the calculated drop checks the assumed one.

V. CONCLUSIONS

For determining the transmission coefficient, air to air, and the outside surface coefficient, mercury thermometers are found to give results of practically the same accuracy as those determined with the thermocouples. Mercury thermometer wells are proven to be of no value in determining surface temperatures, the method finally adopted being to embed the thermometer in the surface so that its center line would lie in the plane of the surface of the material being tested.

Air velocity affects both the air to air coefficient and the outside surface coefficient. For brick and wood surfaces the outside surface coefficients are affected practically the same at the lower velocities, while the coefficient for brick gradually rises above that of wood for the higher velocities.

Humidity has no effect on heat transmission through a brick wall. The air to air coefficient for wood is not appreciably affected by humidity, while an increase in relative humidity of from an average of 71.3% to an average of 96.9% increases the outside surface coefficient 10% as a maximum.

That the results of the Air Velocity and Humidity tests referred to in the Introduction do not check those determined in this investigation is probably due to the method of blowing the air over the material which was apparently not very satisfactory, to say the least.

In making calculations for the heat transmissions of

various walls, it was found that using a value for the outside surface coefficient three times that determined under still air conditions that results were obtained which were in accord with modern practise. This corresponds to an assumption of a wind velocity of 15 miles per hour over the outside surface of the walls.

The tests referred to in Air Space Construction are not sufficient to establish with a great degree of certainty the curve showing the relation between the so-called conductivity of air spaces with regard to the temperature difference across the space. However it is conclusive enough to show that the temperature drop across the air space should be taken into account. And with more tests to establish the curve, the tentative method of calculating the heat transmission for air space construction should give very accurate results.